



Mestrado em Processos Químicos e Biológicos

SABIC's Functional Forms Plant Mass Balance, Production and Waste Analysis, and Sawdust Removal and Elimination

Relatório de estágio apresentado para a obtenção do grau de Mestre em
Processos Químicos e Biológicos

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RESUMO

No âmbito do Mestrado em Processos Químicos e Biológicos, o aluno tem a oportunidade de realizar um estágio para a obtenção do grau de Mestre. Este estágio foi realizado na Saudi Basic Industries Corp (SABIC) mais especificamente no departamento Functional Forms (Specialty Films & Sheets, SF & S, na época) na SABIC Innovative Plastics BV em Bergen op Zoom, Holanda, que é especializada na produção de folhas e filmes de policarbonato.

Este relatório de estágio teve como objetivo desenvolver uma ferramenta que permitisse calcular o balanço mássico de produção por lote, compatível para todos os produtos e todas as linhas. Foi também desenvolvida uma análise de produção das seis linhas nos anos 2014 e 2015 e posteriormente uma análise com maior incidência nos desperdícios produzidos nesses anos, tendo como objetivo determinar um conjunto de ações com o intuito de reduzir a produção dos mesmos. Outra vertente deste estágio consistiu em estudar o problema de produção de serradura nas estações de corte das linhas 1 e 4. A serradura produzida nas linhas de produção fica aderida às folhas de plástico ficando presa entre a película de proteção (*masking*) e a folha, bem como à superfície. Esta limitação tem impedido a SABIC de progredir em vários mercados tais como o das aplicações óticas. Com o objetivo de prevenir a produção de serradura e/ou removê-la do produto foi desenvolvida uma investigação tendo como intuito estabelecer um conjunto de ações de minimização do problema e a sua priorização.

Ao longo deste trabalho foram desenvolvidas várias versões da ferramenta, em Microsoft® Excel, que permite realizar o balanço mássico por lote, chegando a uma versão final, a análise de produção dos anos 2014 e 2015, com maior foco nos desperdícios. A ferramenta teria que simular a realidade o máximo possível, teria que ser compatível com todas as linhas de produção, todas as matérias primas e todos os produtos finais, e, no limite, teria que apresentar uma margem de erro de 2%. Foram desenvolvidas duas versões com bases diferentes, uma tendo como base as dimensões do produto final e outra com base no tempo e velocidade da linha de produção. Por ser mais consistente com a operação real da linha, optou-se por se seguir a versão que tem por base o tempo e a velocidade da linha. A versão final obtida cumpre os objetivos propostos, tendo-se verificado quando testada que se manteve dentro do limite de erro máximo admissível.

Com base na análise de produção dos anos 2014 e 2015, foi possível constatar que ambos os anos tiveram produções muito semelhantes apesar de no ano 2015 se ter produzido menos, sendo que em 2014 houve um rendimento de 83,6% e em 2015 de 83,2%. As linhas que mais produziram foram as linhas 1 e 4 sendo as que também obtiveram um maior rendimento. Também em 2014 foram produzidos mais desperdícios do que em 2015. Previsivelmente as linhas que mais contribuíram para estes valores foram também as linhas 1 e 4. Para realizar uma análise dos desperdícios estes foram divididos em várias categorias quanto à sua causa de produção: qualidade (defeitos no produto produzido), operacional (manutenção), falha (falhas técnicas), mudanças (mudanças de especificações do produto produzido), início de produção (arranque das linhas de produção) e outros (não aplicáveis nas restantes categorias). Concluiu-se que nas linhas 1, 2 e 4 grande parte dos desperdícios produzidos foram devido à categoria mudanças. Na linha número 3, uma linha de apoio e de testes, as causas de desperdícios estavam

equilibradas. A linha 4 para além dos desperdícios causados por mudanças de produção teve como grande causador de desperdícios a categoria operacional, o que faz sentido, já que sendo a linha de produção de produtos óticos é necessária uma grande quantidade de material desperdiçado para limpar os rolos da mesma. Quanto às linhas de produção de filme, linhas 5 e 6, a categoria que mais se destaca é a linha de início de produção. Após estas conclusões realizou-se uma análise mais pormenorizada à categoria de mudanças nas linhas 1, 2, 3 e 4, sendo a mudança de espessura a que mais se destacou. Nas linhas de produção de filme analisou-se a categoria de começo de produção e a maior causa é devido a falhas técnicas.

Durante esta análise foi possível verificar que a produção de corridas longas (*long runs*) ajuda a aumentar o rendimento e a minimizar o material desperdiçado produzido. Além disso, também foi determinado que pequenas mudanças na espessura da folha produzem menos desperdícios do que grandes diferenças na espessura a ser produzida. Não foi possível estabelecer uma correlação entre a quantidade de desperdícios produzida e algumas especificações, tal como uma cor ou espessura em específico. Por outro lado, maiores rendimentos foram obtidos pelas especificações que foram produzidas em maior quantidade ao longo do ano. Isso mostra que é essencial desenvolver um planeamento de produção sempre com o intuito de minimizar as mudanças entre os lotes. No final, uma pequena equipa, envolvendo departamentos de produção e vendas, foi formada e estabeleceu algumas ações para dar continuação a este projeto: racionalização de certas cores em todas as linhas; otimização do planeamento de blocos na linha 1; racionalização de certas larguras na linha 1 e 2; racionalização da largura de 1250 mm e acima de 5 mm de espessura e coletar informações detalhadas sobre as mudanças de espessura e cor na linha 1, 2, 3 e 4; e implementação de um projeto de limpeza dos rolos da linha 4 (já em curso).

O projeto de separação ou eliminação de serradura teve como início coletar informação do funcionamento da linha, informação de projetos anteriores e recolher feedback de várias partes envolvida na produção e na empresa de *coating* a jusante do processo produtivo. Organizou-se também duas reuniões de *brainstorm*, com a participação de várias partes envolvidas no processo de produção. A primeira teve como objetivo identificar quais seriam as causas mais prováveis para a produção de serradura e a segunda para propor possíveis soluções para essas causas e priorizá-las. A partir daí foram desenvolvidas várias ações com o intuito de alcançar as possíveis soluções. Essas ações abrangeram vários campos tanto na eliminação como na tentativa de remoção, nomeadamente a manutenção, *design* das serras, *design* da linha, configurações do processo e aplicação da *masking*. Após várias experiências com o intuito de fazer o despiste das diferentes causas de produção de serradura, concluiu-se que seriam necessários diferentes *designs* de serras para diferentes espessuras de folha produzida, serras essas que têm que estar em bom estado de conservação e disponíveis para serem armazenadas e instaladas de maneira simples. Para isso, desenvolveu-se uma tabela que designa o tipo de serra a ser usada para as diferentes espessuras produzidas, um protocolo com a empresa externa que fornece e faz a manutenção das serras usadas. Também se desenvolveu um novo método de armazenamento e registo das serras, e desenvolveu-se uma ferramenta que permite tirar amostras da serradura produzida aquando dos cortes durante a produção. Por fim, após a maioria

destas medidas terem sido aplicadas, foi possível ver uma melhoria na qualidade dos cortes, principalmente na produção de serradura entre a folha e a *masking*. Por outro lado, ainda se verificou a existência de serradura sobre as folhas, apesar de ser em menor quantidade, sendo que a sua total separação requer uma pesquisa mais aprofundada, que poderá passar por um melhoramento do sistema de sucção instalado nas linhas.

Os dois projetos desenvolvidos durante o estágio irão permitir que a *Functional Forms* otimize a produção, quantificando as diferentes linhas de produção e reduzindo os resíduos. Também irá permitir melhorar a qualidade do produto final, prevenindo e separando a serradura do produto final, reduzindo as queixas de qualidade, permitindo que a SABIC cresça em diferentes mercados, nomeadamente no mercado de produtos com aplicações médicas, visores de aparelhos eletrônicos, visores de meios de transporte, já que estes requerem folhas de policarbonato com qualidade ótica.

Devido a razões de confidencialidade, por parte da SABIC, não foram divulgados valores das quantidades produzidas no capítulo 3 (*Production and Wastes Analysis*). Assim como não foram divulgadas as empresas externas, com quais a SABIC tem parceria, nem as marcas dos materiais usados no capítulo 4 (*Sawdust Removal and Elimination*), no presente relatório de estágio.

Palavras-Chave: Plástico, Policarbonato, Extrusão, Serradura.

ABSTRACT

In the scope of the Masters in Chemical and Biological Processes, the student has the opportunity to undertake an internship to obtain the Master's degree. This internship was performed at Saudi Basic Industries Corp (SABIC) more specifically for the Functional Forms plant (Specialty Films & Sheets, SF&S, at the time) in the SABIC Innovative Plastics B. V. in Bergen op Zoom, The Netherlands, which is specialized in the production of solid polycarbonate sheets and films.

This internship report aimed to develop a tool to calculate the mass production balance per batch, compatible for all products and all lines. An analysis of the production lines of Functional Forms plant was also developed, in the years 2014 and 2015, and later an analysis with greater incidence in the wastes produced during those years, aiming to determine a set of actions with the intention of reducing the production of wastes. Another aspect of this stage was the problem of the production of sawdust in the cutting stations on lines 1 and 4. The sawdust produced in the production lines sticks to the plastic sheets getting stuck on the surfaces and between the masking and the sheet. This phenomenon has prevented SABIC from progressing in several markets with optical applications. In order to prevent the production of sawdust and / or to remove it from the product, an investigation was developed aiming at establishing a set of actions and prioritizing them.

Throughout this work several versions of the tool were developed, in Microsoft® Excel, which allows to perform the mass balance by batch, arriving at a final version, and the production analysis of the years 2014 and 2015 and with greater focus on waste. The tool would have to simulate the reality as much as possible, it would have to be compatible with all production lines, all raw materials and all final products, with a margin of 2% error. Two versions were developed with different bases, one based on the dimensions of the final product and another based on the time and speed of the production line. As the objective, as already mentioned, would be to simulate the reality as much as possible, it was chosen to follow the version that was based on the speed of the line. At the end, a version that fulfilled the proposed objectives was achieved, and when tested it remained within the limit of maximum error.

Based on this analysis, it was possible to verify that both years had very similar productions, although in the year 2015 there was fewer production. In 2014 there was an 83.6% yield and 83.2% in 2015. The lines that produced the most were lines 1 and 4 and those are the ones that also obtained a higher yield. Also, in 2014 were produced more wastes than in 2015. Predictably the lines that contributed the most to these values were also lines 1 and 4. In order to carry out an analysis of the waste produced, these were divided into several categories as to their production cause: quality (defects of the product being produced), operational (maintenance), failure (technical failures), changes (changes in specifications of the product being produced), start of production (start of production lines) and others (not applicable in other categories). It was concluded that in lines 1, 2 and 4 a large part of the waste produced was due to changes between batches. Line number 3, being a test line, the causes of waste were balanced. In addition to the wastes caused by changes during production, line 4 had as its main cause of wastes production the operational category. This mainly occurs because line 4 is the production

line of optical products and requires a lot of wasted material to clean the rolls. As for the film production lines, lines 5 and 6, the category that stands out the most is the starting of production. After these conclusions, a more detailed analysis was carried out on the category of changes in lines 1, 2, 3 and 4, being the change of thickness being the most outstanding. In the film production lines, the start of production category was analysed, and the biggest cause is technical failure. During this analysis was possible to verify that producing long runs helps in increase the yield and minimize the production wasted material. Also, although is not presented here, was also determined that small changes in the thickness of the sheet produce less scrap than big jumps in the thickness. It was not possible to perceive a correlation between the quantity of scrap produced and some specification, like a specific colour or thickness. In the other hand, higher yields were achieved by the specifications which were produced in most quantity during the year. This shows that it is essential to develop a production planning always with the intention of minimizing the changes between batches. In the end a small team, involving both manufacturing and sales departments was formed and set some actions to follow up this project: rationalization of certain colours in all lines; optimize block scheduling in line 1; rationalization certain widths in line 1 and 2; rationalization width 1250mm and above 5mm gauge and gather detailed information according to thickness and colour changes in line 1, 2, 3 and 4; project Roll cleaning (already on going).

The separation or elimination of sawdust project had as its starting point to gather information on the operation of the line, information from previous projects and feedback from various parties involved in the production and post production. It was also organized two brainstorming sessions, with the participation of several parties involved in the production process. The first was to designate which would be the most probable causes to produce sawdust and the second to designate possible solutions to these causes and prioritize them. From there, several actions have been designed to reach possible solutions, those actions covered several fields in both elimination and attempted removal, namely maintenance, saw design, line design, process settings and masking application. After several experiments in order to make the different causes of sawdust production known, it was concluded that different saw designs would be necessary for different sheet thicknesses, which need to be in good condition and available to be stored and installed in a simple way. For this, a table was developed that designates the type of saw to be used for the different thicknesses produced, and a protocol with an external company that provides new saws and maintains the used ones. A new method of storing and registering saws has also been developed, and a tool has been developed that allows to take samples of sawdust produced by the cuts during production. Finally, after most of these measures were applied, it was possible to see an improvement in the quality of the cuts, mainly in the production of sawdust between the sheet and the masking. In contrast, there is still sawdust on the sheets, despite being in a smaller quantity, thus its total separation requires a more detailed investigation, which may pass by improving the vacuum system installed on the lines.

Both projects, developed during the internship, will allow the Functional Forms plant to optimize production, by quantifying the different streams of production and reducing wastes. It

Abstract

SABIC's Functional Forms Plant Mass Balance, Production and Waste Analysis, and Sawdust Removal and Elimination Optimization

will also improve the quality of the product by preventing and separating the sawdust of the final product, dropping the quality complains, allowing SABIC to grow in different markets.

Along the present Master thesis due to confidentiality reasons of the company SABIC, in chapter 3 (Production and Wastes Analysis) volume values were not published. As well, in Chapter 4 (Sawdust Removal and Elimination) neither the identity of the external companies, with which SABIC has a partnership, nor the brands of the materials used, were published.

Keywords: Plastic, Polycarbonate, Extrusion, Sawdust.

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GLOSSARY

BoZ	<i>Bergen op Zoom</i>
CAGR	<i>Compound Annual Growth Rate</i>
CCD	<i>e-coupled device</i>
CIS	<i>onwealth of Independent States</i>
CUT	<i>uous use temperature under unstressed state</i>
EMEA	<i>Europe, Middle East and Africa</i>
EU-27	<i>27 countries of European Union during the period of 2007-2013</i>
FDA	<i>Food and Drug Administration</i>
FF	<i>Functional Forms</i>
GF	<i>Glass Fiber</i>
GP	<i>Gas Permeable</i>
ISEC	<i>Instituto Superior de Engenharia de Coimbra</i>
SABIC	<i>Saudi Basic Industries Corp</i>
SF&S	<i>Specialty Films & Sheets</i>
TTFG	<i>Final product</i>
UL	<i>Underwriters Laboratories</i>
US	<i>United States of America</i>
US\$	<i>United States dollar</i>
UV	<i>Ultraviolet radiation</i>

1. INTRODUCTION

In the scope of the Masters in Chemical and Biological Processes, the student has the opportunity to undertake an internship or to develop a final course project/dissertation. Having the preference for an internship, and preferably abroad, the student applied to an online internship offer at Saudi Basic Industries Corp (SABIC) more specifically for the Functional Forms plant (Specialty Films & Sheets, SF&S, at the time) in the SABIC Innovative Plastics B. V. in Bergen op Zoom, The Netherlands, having been accepted by the company.

This resulted in a partnership between the Instituto Superior de Engenharia de Coimbra (ISEC) and the company SABIC, with the aim of placing the student in contact with the business environment, performing tasks associated with process and quality optimization. The internship lasted 6 months, starting in October 2015 and ending in March 2016.

The internship had as main objectives the optimization of the processes to separate and/or eliminate the sawdust, the elaboration of a tool allowing the calculation of the mass balance of each line per batch and a global mass balance and wastes analysis of the Functional Forms production lines, one of the site's plants.

In this chapter there is a short introduction where all topics of interest related to the internship and to the Functional Forms plant products, polycarbonate sheet and film, are mentioned.

Follows the presentation of the factory, worldwide and particularly in Bergen op Zoom (BoZ). It is worth noticing, SABIC, is one of the plastic and polycarbonate sheets and films market leaders in the world.

1.1. Company Presentation

SABIC is a Saudi diversified multibillion-dollar manufacturing company, active in chemicals and intermediates, industrial polymers, fertilizers, and metals. SABIC is the largest listed company in the Middle East, with operations in more than 50 countries and over 40000 employees worldwide, those locations can be seen in Figure 1.

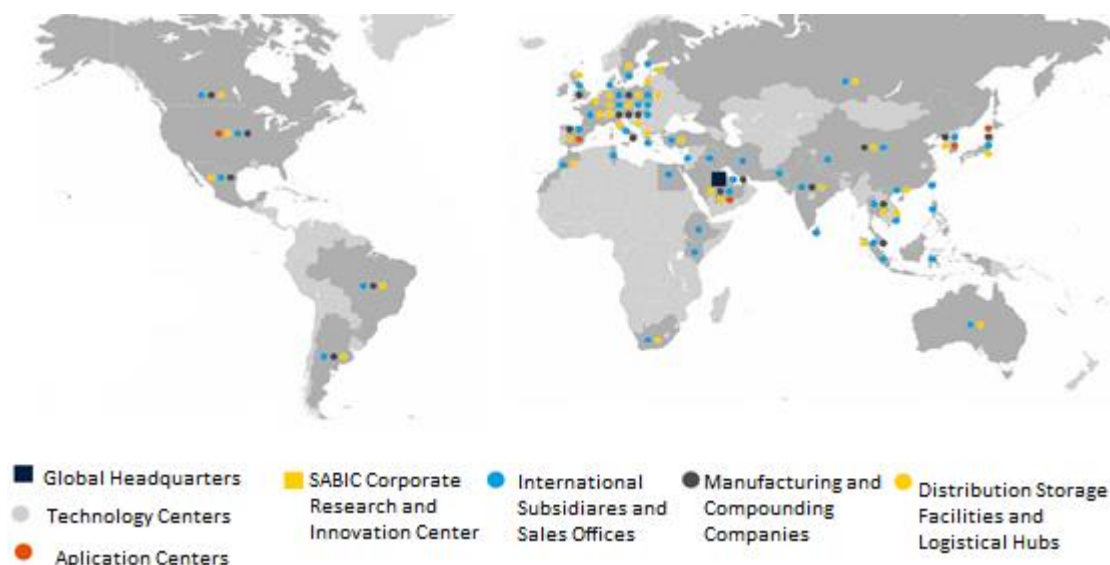


Figure 1 - SABIC's locations around the World. Adapted from: (SABIC, 2016)

Ranked among the world's largest petrochemicals manufacturers, SABIC is a public company based in Riyadh, Saudi Arabia. Seventy percent of the Company's shares are owned by the Saudi Arabian government, with the remaining 30% held by private investors in Saudi Arabia and other countries of the Gulf Cooperation Council.

SABIC is currently the second largest global ethylene glycol producer, the third largest polyethylene manufacturer, the fourth largest polyolefins manufacturer, and the fourth largest polypropylene manufacturer. SABIC is also the world's largest producer of granular urea, polycarbonate, polyphenylene and polyetherimide.

On May 21, 2007, SABIC acquired General Electric's Plastics division, in a US\$11,600 million cash deal, including US\$8,700 million of its liabilities, and launched SABIC Innovative Plastics (New York Times, 2007). As of 2017 SABIC is the world's 117th largest corporation on the Forbes Global 2000 ranking, with sales revenues of US\$50,400 million, profits of US\$4,800 million and assets standing at US\$84,500 million (Forbes, 2017).

In Europe, SABIC has thirteen world-class petrochemical production sites. Engineering Thermoplastics and Specialties are produced in Bergen Op Zoom, Enkhuizen and Raamsdonksveer (The Netherlands), Thornaby (United Kingdom), Fosses (France), Pontirolo and Olgiate Olona (Italy), Cartagena (Spain) and Wiener Neustadt (Austria). Plastics and chemicals are produced in Geleen (The Netherlands), Genk (Belgium), Teesside (United Kingdom) and Gelsenkirchen (Germany).

The Bergen op Zoom site (Figure 2) hosts eight production plants of Lexan (a resin based on polycarbonate and polyetherimide), Noryl (a resin based on polyphenylene ether and polystyrene), Valox (a blend of polymeric materials of semi crystalline structure based on polyesters, mainly polyethylene terephthalate), Xenoy (a blend of semicrystalline polyester and polycarbonate) and Xylex (a blend of polycarbonate and amorphous polyester). One of the site's plant is the Functional Forms, which is specialized in the production of solid polycarbonate sheets and films. The plant has six lines, line 1 and 2 produce solid sheets, line 4 produces solid sheets with optical quality, lines 5 and 6 produce films and line 3 has the capability to produce both solid sheets and films.



Figure 2 - Satellite image of SABIC innovative Plastics BV site and Functional Forms plant in Bergen op Zoom. Adapted from: (Google Maps, 2017)

As SABIC is changing its informatics system, a tool to calculate the Functional Forms plant line's production, per batch, was needed. Also, the necessity to prepare part of the mass balance tool elaboration was detected, and in tune with that project, a production and waste analysis was required. The presence of saw dust in the final product prevents SABIC to grow in the markets with optical applications, so there was the necessity to optimize the removal and elimination of sawdust from the final product.

1.2. The Production of Solid Sheets: aspects related with the process, market, and amount of money

1.2.1. Plastic Industry Market

Worldwide, the 2008 and 2009 global economic crisis affected the plastic industry, however since 2010, it has been recovering consistently. Global plastics production increased by 10 million tons (3.7%), to around 280 million tons in 2011, continuing the growth pattern that the industry has enjoyed since 1950, approximately by 9% per year (Association of Plastics Manufacturers, 2012). Competition in the industry is growing, plastics markets are progressively shifting towards Asia, which is characterized by over-average growth rates and is rising in production capacity. The world's plastic production since 1950 is characterized in Figure 3 (Association of Plastics Manufacturers, 2012).

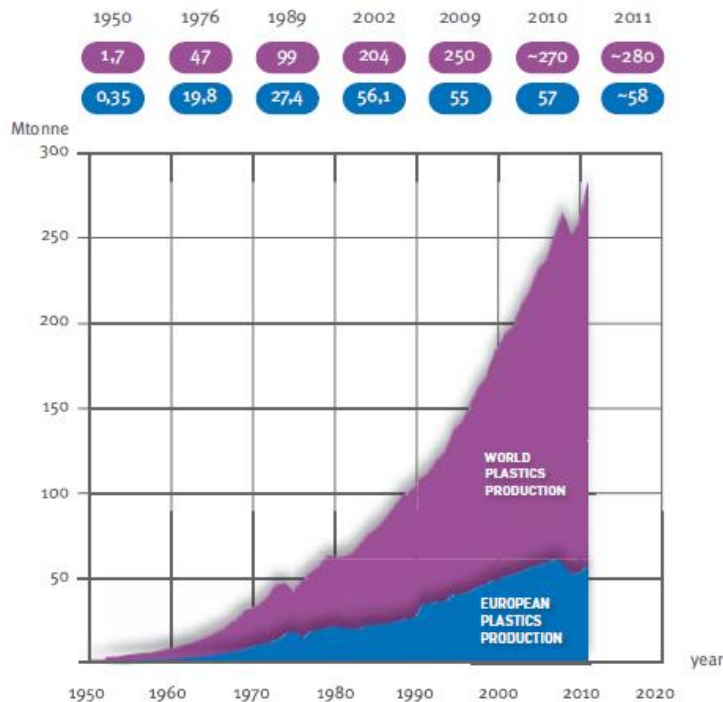


Figure 3 - Worldwide and European Plastics Production 1950-2011. Source: (Association of Plastics Manufacturers, 2012)

1.2.2. Plastic Industry Market in Europe

Such as the rest of the World's, Europe's plastic production has been rising, except during the global financial crisis years (2007-2009). In 2011, the EU-27 plastics industry had a 0.3% increase in their turnover to over 89,00 million euros. Converters had a greater growth, they experienced an increase to almost 194,000 million euros (1.9%). Although the global financial crisis, the producing sector workforce remained relatively stable, with 167,000 employees and converters employing 1.23 million European citizens. In total, the industry employs a workforce of 1.45 million, including 53,000 from the plastics machinery industry (Association of Plastics Manufacturers, 2012).

1.2.3. Polycarbonate Sheet Industry Market

Polycarbonate was introduced in 1957 as a replacement to metals. Although it couldn't always compete with metal on a raw material cost per pound, the molded polycarbonate parts have the advantage of not requiring a secondary finishing, which is a major labour cost saving (Margolis, 1985).

Polycarbonate was one of the principal plastics produced during the period of 1995-2000 in the engineering plastics sector. During that period, it averaged an annual worldwide consumption growth of 15-20%. Nevertheless in 2001 there was a major contraction in demand for this plastic with world consumption falling 6-7%, this occurred not only due to the downturn in major markets such as automotive, construction and electrical and electronics, but also to relatively high stocks that converters had built up in previous years. The major decline in 2001

was registered by the United States (US) market, with 16%, followed by Japanese consumption lower by over 14% and Europe just over 6.5% (Platt, 2003).

Next year, in 2002, the world demanding recovered 5.7%, with the Asia Pacific recording the fastest growth, and Western Europe demand grew by 6.3%, while consumption growth in the US and Japan was much more unassertive (Platt, 2003).

Table 1 shows the major users of polycarbonate during part of the period mentioned above. More than one quarter of total world consumption are the consumer products, such as optical data media appliances. Then it is followed by electrical and electronics, medical applications, and automotive. Other markets, comprising packaging, optical lenses and sports equipment, are about 11 % of total consumption (Platt, 2003).

Table 1 - World consumption of polycarbonate, by sector, for the period 1999-2002. Adapted from: (Platt, 2003)

	1999		2000		2001		2002	
	1000 tons	%	1000 tons	%	1000 tons	%	1000 tons	%
Automotive	290	19.0	314	18.2	269	16,6	283	16.5
Electrical & Electronics	402	26.3	431	25.0	401	24.7	426	24.9
Consumer products	358	23.5	458	26.5	471	29.1	497	29.0
Medical	308	20.2	323	19.0	302	18.6	323	18.8
Other	168	11.0	195	11.3	178	11.0	185	10.8
TOTAL	1526	100.0	1726	100.0	1621	100.0	1714	100.0

In the middle 2010's, the largest market for polycarbonate was Asia-Pacific, being about 60% of the global polycarbonate market demand. The Asia-Pacific market development is due to the shift of various end-use industries of polycarbonate from western regions to the Asia-Pacific. The advantages, for those industries, in this developing market, are the low labour cost, easy availability of raw materials, and lack of stringent regulations. Western Europe is the second-largest market for polycarbonate, followed by North America, and at last, Latin America (Markets and markets, 2015; Wiley-VCH, 2016). These markets' shares are represented in Figure 4.

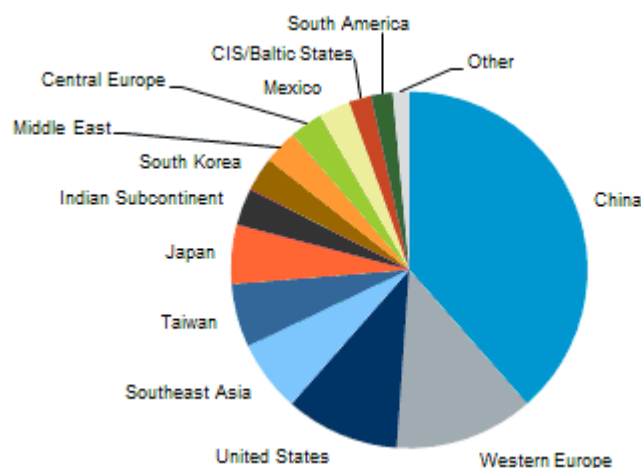


Figure 4 - World consumption of polycarbonate resins in 2015. Adapted from: (IHS Markit, 2016)

Globally, consumption is not dominated by any single application. The largest market application in the US is the automotive/transportation, it amounts to 24%, in Western Europe is building and construction (sheet and film) with a total of 25%, in China the largest is the electronic/electrical market with 30% of the market, and the electronic/electrical market is also the largest in Japan with 27% of the market (IndustryARC, 2015).

The polycarbonate resin market in 2015 worth more than US\$12,000 million and is expected to reach US\$16,400 million in 2020. While the European Polycarbonate Market size in terms of value of polycarbonate was estimated to be US\$1,900.0 million in 2014 and is projected to grow at a CAGR (Compound Annual Growth Rate) of about 5% from 2014 to 2019 (Business Wire, 2015).

Forecast growth rates for consumption of polycarbonate vary widely by region but the global consumption growth rate will average about 3% during 2015–20. Also, is predicted that Northeast Asia is going to continue to be the largest consumer of polycarbonate resins and will be one of the fastest-growing regions, averaging growth of about 4% per year, driven by 5% per year growth in China. Asia's growth will be followed by the CIS (Commonwealth of Independent States) and Baltic States and Southeast Asia at around 3.5–4.5%. (IHS Markit, 2016).

The global polycarbonate industry is dominated by two producers whose capacities accounted about for 54% (about 27% each) of world capacity: Bayer (Bayer Material Science) and SABIC Innovative Plastics. They were followed, in 2012, by three other major companies: Mitsubishi (12%) (Mitsubishi Chemical, Mitsubishi Gas Chemical and Mitsubishi Engineering Plastics); Teijin (10%) and Styron (6%) (Wiley-VCH, 2016).

The requirement for large initial investment, access to technological licensing, possible start-up difficulties, and the establishment of efficient and effective marketing, are major obstacles to enter the polycarbonate resin business, making it difficult to compete with the polycarbonate

manufacture giants. It is necessary to continue to develop improved polycarbonate resins for the growing medical/ophthalmic applications and growing optical lens markets, including digital camera lenses and other uses requiring a high refractive index and low birefringence (IHS Markit, 2016).

1.3. Polycarbonate Solid Sheet – characteristics and specifications

The versatility of polycarbonate makes it suitable for many engineering applications, as stated in section 1.2.3. Polycarbonates are polyesters resulting from the polycondensation of carbonic anhydride and a bisphenol. Polycarbonates are amorphous and highly transparent thermoplastics with excellent impact strength, and low resistance to ultraviolet (UV) and weathering. When extruded in sheet form, its optical and impact properties render this material as a strong candidate for a wide range of glazing applications (Biron, 2007; General Electric Company, n.d.). High quality polycarbonate sheets are characterized by its dimensional stability at elevated temperatures; inherent “water-clear” transparency; high impact strength; flame resistance; FDA (Food and Drug Administration) compliance; lightweight and formability (SABIC, 2009), properties that will be discussed in the next chapters.

1.3.1. Thermal Behaviour

The continuous temperature in an unstressed state (CUT) is generally estimated from 90°C up to 125°C for gas permeable (GP) grades and up to 140°C for heat-resistant polycarbonates, if the softening or melting temperatures are higher. The ultraviolet temperature indices of specific grades can range from 65°C up to 130°C (Biron, 2007).

Figure 5 displays two examples of modulus retention *versus* temperature for a neat and a glass fiber (GF) reinforced polycarbonate; the two curves are almost the same, having a rapid fall at about 140-145°C (Biron, 2007).

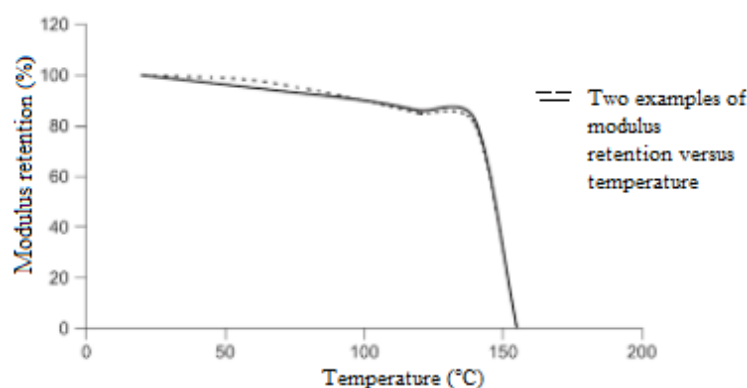


Figure 5 - Polycarbonate examples of modulus retention (%) *versus* temperature (°C).

Adapted from: (Biron, 2007)

At low temperatures, the behaviour can be reasonably good down to -20°C , or even less, depending on the grades. Rigidity slowly increases when the temperature decreases down to -60°C , as seen in Figure 6.

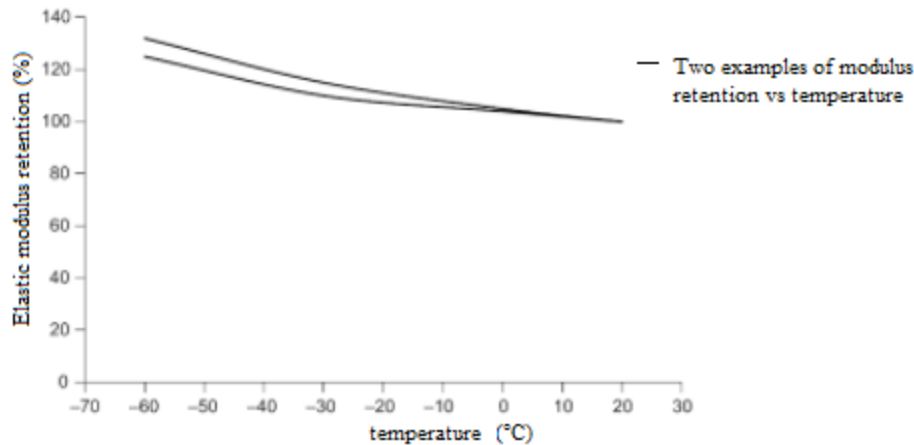


Figure 6 - Polycarbonate examples of elastic modulus retention (%) *versus* temperatures ($^{\circ}\text{C}$).
Adapted from: (Biron, 2007)

Glass transition temperatures are high, around 150°C , for some grades and from 160°C to 200°C , for heat-resistance grades (Biron, 2007).

1.3.2. Optical Properties

The use of polycarbonate as a glazing material and both ophthalmic and automotive lenses has occurred because of its transparency, ductility and high heat distortion temperature. Amorphous polycarbonate is transparent with light transmittance ranging from 80% to 91%, a haze of roughly 0.7 to 1.5% and a refractive index about 1.580-1.586 (LeGrand & Bendler, 2000).

One of the grades with optical quality is the polycarbonate sheet Lexan Thermoclear, by SABIC. This sheet is almost opaque to radiation in the UV and far infra-red region, although it transmits light very well. This useful shielding property can prevent discoloration of sensitive materials and reduces the heat build-up, as presented in Figure 7 (General Electric Company, n.d.).

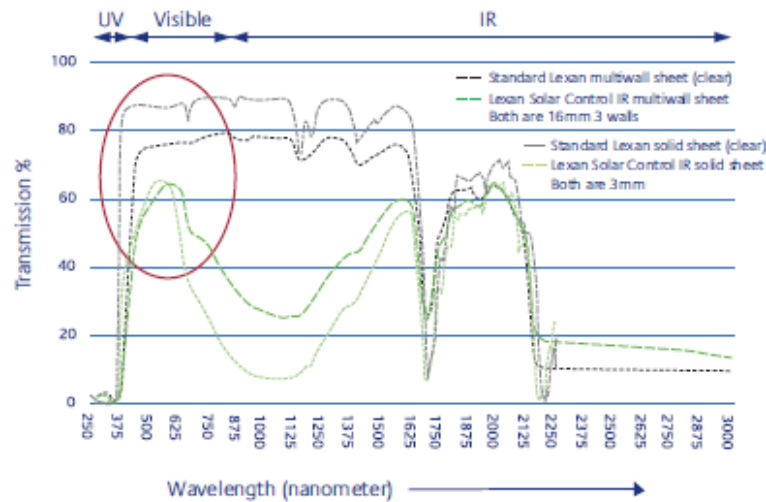


Figure 7 - Light transmission (%) *versus* light wavelength (nanometer) of a Lexan sheet.
Source: (SABIC, 2009)

1.3.3. Mechanical Properties

A hard and tough material such as polycarbonate is characterized by high modulus, high yield stress, high elongation at break and high ultimate strength (Lampman, 2003). So, as expected the mechanical proprieties of polycarbonate sheets are similar, with relatively high elongations at break but much more limited strains at yield. Modulus and hardness are in a medium range and impact strengths are excellent. The abrasion resistance of polycarbonate sheets depends on the roughness, type and morphology of the opposing sliding surface. The coefficients of friction range are from 0.10 to 0.21 (Biron, 2007).

Alterations due to moisture exposure are weak, the shrinkage and coefficient of thermal expansion are rather low and polycarbonate sheets also have a good creep resistance. As stated by Biron (2007), the creep strengths for failure after 10000 h, of some polycarbonate sheets grades, with an engineering tensile strength of 67 MPa, are:

- 15 MPa at 120°C, which is 22% of the engineering tensile strength;
- 20 MPa at 100°C, which is 30% of the engineering tensile strength;
- 30 MPa at 80°C, which is 45% of the engineering tensile strength;
- 38 MPa at 60°C, which is 57% of the engineering tensile strength;
- 45 MPa at 23°C, which is 67% of the engineering tensile strength.

For a 2-year outdoor exposure of transparent polycarbonate sheet, the retention of impact strengths can be 4% for a no stabilized grade and 100% for a UV-stabilized grade. The optical properties for the same sheet in the same conditions are for no stabilized grade 82% for transmittance, 20% for the haze and 20 for the yellowing and for a UV-stabilized grade are 87% for transmittance, 15% for the haze and 6 for the yellowing (Biron, 2007).

Polycarbonate sheets have also a better resistance to impact than glass and acrylic. Figure 8 shows the results of an experience to test the impact resistance due to a falling steel dart with 2.3 kg and 25.4 mm diameter (SABIC, 2009).

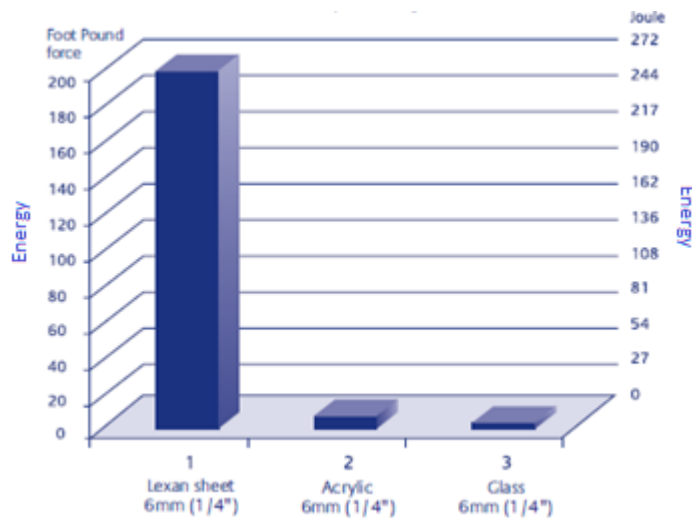


Figure 8 - Impact strength resistance for different materials. Adapted from: (SABIC, 2009)

1.3.4. Chemical Resistance

Although the polycarbonate sheets they have generally good chemical resistance at room temperature to dilute acids, oils, greases, aliphatic hydrocarbons and some alcohols, they present low resistance to aldehydes, ketones (can cause stress-cracking and severe crystallisation), esters (can cause crystallisation), ethers, aromatic and halogenated hydrocarbons (severe stress-cracking agents), organic and mineral concentrated acids and bases, amines (surface crystallisation and chemical attack) and phenols (Biron, 2007; Astrup, n.d.; The plastic shop, n.d.)

1.3.5. Electrical Properties

Polycarbonate sheets are good insulators even in wet environments with high dielectric resistivity, fair rigidities and low or moderate loss factors. This characteristic led to its application in the electric industry (Biron, 2007).

1.3.6. Water Absorption

Unlike other materials, whose mechanical properties are affected by moisture or water absorption, polycarbonate's mechanical properties are not affected. This is the main reason why these sheets are used in glazing applications.

Polycarbonates absorb small quantities of water, less than 0.6%. However, when polycarbonates are washed with hot water, after a long period of time, they may begin to decompose reducing the ability of polycarbonate sheets to resist impact or shock.

Polycarbonates offer limited retraction during molding and its inability to absorb moisture/ and humidity makes it to have a good dimensional stability especially in a humid atmosphere. During injection molding, it should be subjected to higher pressures of between 800 bars and 1800 bars (Excelite, 2017).

1.4. Component Manufacturing Process

The first step of the polycarbonate manufacturing process is to receive, inspect and store the polymeric raw materials. Before extrusion, the polymer may be blended with additives, colour pigments, flame retardants, reinforcements, etc., depending on the grade which is going to be produced. Due to moisture some resin products must be dried before extrusion to prevent polymer degradation. Once the ingredients are properly prepared, the formulation is fed into the extruder, where it is melted, mixed and delivered to the die. Then, the product is cooled, solidified, shaped and pulled away from the extruder at a constant velocity by the rollers. Next, secondary operations may be performed, like masking application, flame treatment, cutting, etc. Finally, the final product is inspected, packed and shipped. All this process is represented in Figure 9 (Giles *et al.*, 2005).

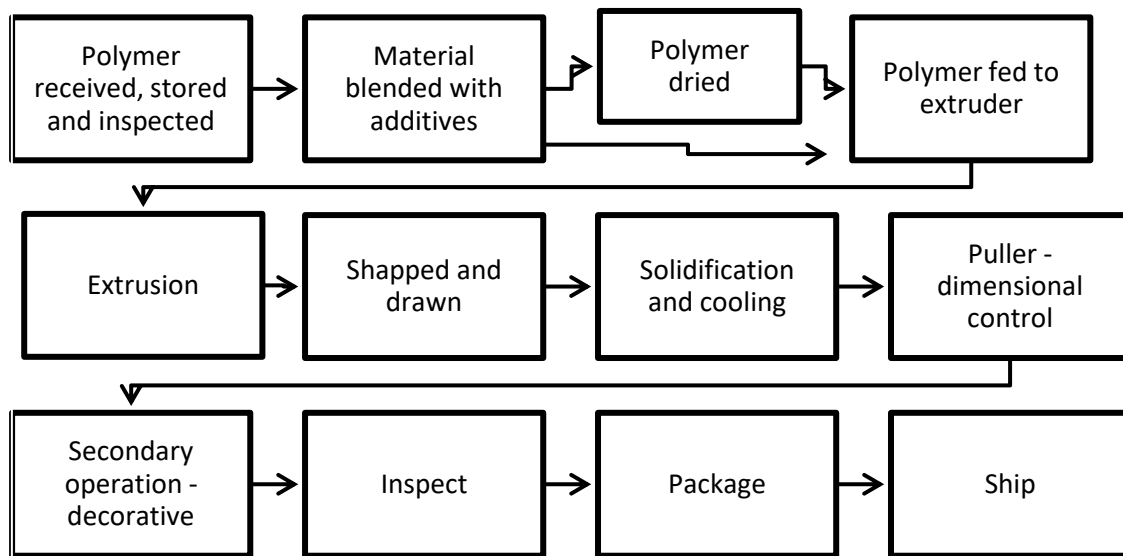


Figure 9 - Diagram of a basic industrial resin extrusion process. Adapted from: (Giles *et al.*, 2005).

Usual molding methods for polycarbonate sheet production are injection molding, compression molding, and a fusion of both methods, injection-compression molding.

1.4.1. Calendering Process

The term 'calender' means 'to press (plastic) between rollers or plates to make smooth and glossy or glazed or produce thin sheets. This process is used to produce rolled sheets of specific thickness and final appearance in many industries, such as the plastics, rubber, paper and steel industries. In the plastics industry, the calendering of molten polymers is a process to produce continuous sheet or film by squeezing the melt between 3 to 6 heated counter-rotating rolls in a 'L' or 'Z' arrangement. The forming operation is completed by the calender itself and is

usually followed by additional treatment of the plastic sheet or film produced. Figure 10 shows an example of this industrial process.

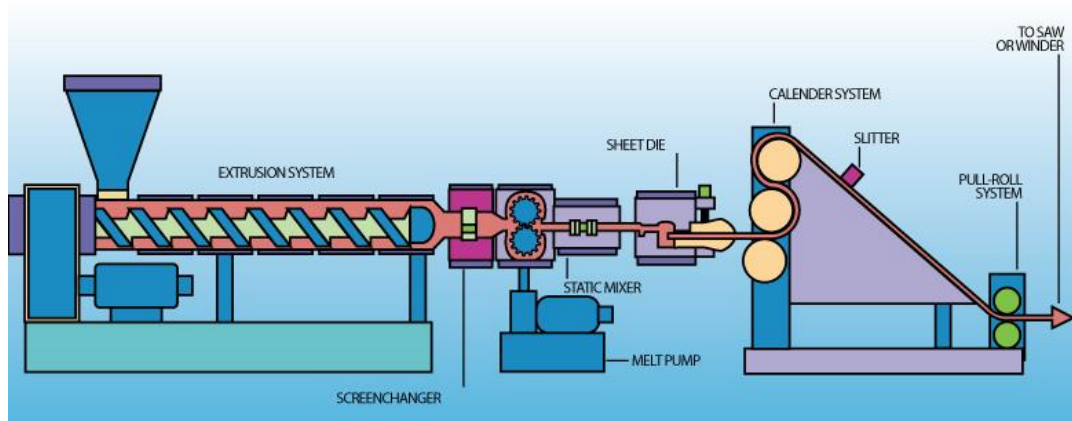


Figure 10 – Illustration of an example of a plastic injection molding machine. Source: (Excelite, 2017)

The molten material is fed to the calender rolls from a large extruder. The rolls are internally heated. In the case of a four-roll configuration there are three areas of contact (nip regions) between two rolls, which reduces the polymer melt thickness gradually while making a wider film. The difference in speed between two adjacent rolls is the friction, which combined with temperature gives increased shear mixing, allowing the transfer of the melt from one roll to the next. A polymer accumulation (bank) of material is formed in front of each nip which feeds the nip. For each rotation of the roll, only a small portion of the bank enters the nip, thus the material in the bank is exposed to high temperatures for long times (residence time), while the material that passes through the nip does so for short times but at high shear rates. Also, properties such as adhesion to the rolls and some form of melt strength are important as the material exits the last nip and is drawn down to the final sheet thickness on take-off rolls cooling the film to room temperature. The most important for hydrodynamic analysis for determination of flow variables, such as pressures and forces which affect the final film properties, is the final nip region.

Calender sizes range up to 250 cm in width and 90 cm in diameter, with polymer throughputs up to 4000 kg/h. Roll speeds may be as high as 2 m/s for certain thin flexible films (thickness less than 0.1 mm). In terms of capital investment in machinery, calendaring lines are very expensive. Film and sheet extrusion are competitive processes because the capital investment for the extruder itself is only a fraction of the cost of a calender. Nevertheless, the high quality and volume capabilities of calendaring lines make them advantageous for many types of products, especially for temperature sensitive materials (Thomas & Yang, 2009).

1.4.2. Extrusion Conditions

For a single screw extruder, the feed section length should be 30-40% of the screw length, the transition 20-40% of the length, and the metering section is the rest. Polycarbonate melt viscosity is more temperature sensitive than shear sensitive, per instance, increasing the melt

temperature from 235°C to 265°C decreases the viscosity by 2.6 times, while increasing the shear rate from 100 to 400s⁻¹ over the same temperature range reduces the viscosity 1.5 times. The optimum melt temperature at the die is between 249°C and 266°C. The die gap is usually set 5-20% greater than the desired final dimension (Giles *et al.*, 2005).

1.5. Inspection Methods

During the production process it is very important to inspect the quality of the manufactured product. This is an important area that should be thoroughly analysed and studied to obtain the desired performance of the complete production line and its parts. First, it is necessary to determine what is required to control and how to approach it; some examples are in Table 2. With proper controls, it is possible to achieve different advantages, such as better economics, improved quality of product, maximized output rate, plastic wastes reduction by minimizing tolerances, reduced setup times, utilities savings and reduced scrap (Rosato, 1998).

Table 2 - Examples of process variables to control and instrument sensors that could be used to control them. Adapted from: (Rosato, 1998)

Process variables	Instrumentation
Temperature	Thermoelements; Resistance elements, Radiation recorder
Pressure	Strain gauges, Resistance elements
Rotational speed	A-c/d-c generators, Incremental counters
Weight	Strain gauges, Piezo elements
Velocity	A-c/d-c generators, Incremental counters, Correlators
Torque	Strain gauges, Scales
Time	Impulse counters
Logic state (on/off)	Switches

Controls demand a high level of expertise from the processor. They provide closed-loop control of temperature, pressure, thickness, etc, and maintain pre-set parameters, monitor and correct equipment operations contributing for a process optimization (Rosato, 1998).

Most processes operate better when most functions occur in a desired time sequence or at prescribed intervals of time. Nowadays electronic logic and timing devices are used based on the programmable logic controllers. Microelectronic controls have eliminated many potential human errors in setting production lines, such as data entry errors and mistakes due to insufficient extrusion knowledge. They represent a major opportunity to improve the reliability

of setting the process while eliminating manual machine adjustments, which can penalize the output rate and quality of final products. They also increase the number of controlled variables and have improved the user interface resulting in a more reliable operating line which results in a process optimization (Rosato, 1998).

1.5.1. Static Process Control

Static process control is increasing in importance as the techniques are adapted to use by the industry. The introduction and integration of computer control allow real time data collection and its benefits are being realized by the industry. The continuous nature of the extrusion process is a barrier to apply statistical process control but can be overcome and its benefits are worth it (Kent, 1998).

1.5.2. Self-Centring and Measurement Systems for Pipes

The linkage of control systems to inspection devices is widely used and such investments have very short payback times. A saving of 3% of material, on a pipe manufacturing rate of 800 kg/h, would save more than £25,000 per year on an extrusion line that costs £250,000. The typical system consists of an ultrasonic wall thickness meter mounted on a circular open frame track enclosing the pipe, that is linked to a computer control system which displays the wall thickness and distribution of the material in the pipe. Data monitoring of the output also provides records proof of conformance to specification. This system is crucial in achieving both process and quality control (Kent, 1998).

1.5.3. Measurement of Profiles and Computer Aided Systems for Rapid Inspection

For general profile production, it is currently possible to perform on-line measurement or detection of parameters such as gloss, colour and gross surface faults. Although machine control can operate for corrective actions, this is difficult, and most systems operate with a set limit alarm only. Measurement optical systems are preferred because the general profiles dimensions are so critical that the application of on-line measurement and control is complex, and non-contact is important. Techniques as laser light interstation and a charge-coupled device (CCD) array camera to measure the topography of profile products can be used to provide a dimensioned surface profile, but application to complex profiles with re-entrant features is difficult and internal features cannot be measured. The usage of new computer based video and image sensing devices can provide measurement data in minutes, that otherwise would take hours of inspection and labour time. This reduces dramatically the inspection load, remove the need for dedicated inspectors and allow process control to be accepted by the operator (Kent, 1998).

1.5.4. Gravimetric Feeding for Extrusion

Gravimetric control is the continuous monitoring of the 'loss in weight' of material at the feed hopper end of the extruder and the use of this information for inline control of the extruder based on the detected material usage. This allows fine control over the materials usage and the process itself to give improved productivity and competitiveness. The extruder screw remains the metering device, but the 'loss in weight' information is used to set the screw speed to achieve a constant materials usage rate. This enables the close control of the product average thickness or weight per unit length. Each individual ingredient is weighted delivering precise and homogeneous blends, giving high batch accuracy (Kent, 1998).

1.5.5. Fault Finding

Defect rectification and problem solving in the extrusion process are extremely complicated processes. Processing problems are often difficult to solve, and cause and effect are often not simply related. A single fault may be the cause of many observed defects or many faults may be the cause of a single defect. True fault finding has traditionally been a specialized field and has depended on the knowledge and presence of experts for success (Kent, 1998).

1.6. Quality Control Methods

As stated by Holister & Salking (1973), quality is a process, not a destination. Therefore, in order to produce composite components, quality control activities must be performed continuously from initiation to completion to ensure reproducible high-quality production. This quality control is even more necessary for composite materials than for homogeneous materials, because the final product is manufactured from various intermediate material components. All parts of the process must be inspected for conformance to material specifications, since the incoming raw material, the production process itself to the final product. As a final check, some combination of destructive, non-destructive, and proof testing of the finished article must be performed (Holister & Salking, 1973).

1.6.1. Types of Surface Defects

Plastics are manufactured with the purpose of being useful to society, the product is required to satisfy not only physical and functional needs laid down, but also should respond to the sensitivity of those who contact with it (Pinner & Simpson, 2003).

In the first stages of assessing plastics surfaces, reliance is placed on human senses, the tendency is to regard the human inspector as the 'automatic' system and use it as a standard for comparison. As demands for quality and uniformity become more rigorous, it is vital to limit and localize defects, and to start, is necessary to identify and classify them. A polycarbonate sheet could have different types of defects in many sizes and shapes, which are illustrated in Figure 11. Foreign matter can be present in the sheet which is a result from a contamination of the raw materials used. Pinholes can be observed as a consequence of trapped air. Scratches,

marks made on surfaces by hard objects can exist in the polycarbonate sheets. Segregation, which is a defect in the transparency and unevenness, dents or protuberances at the surface can also be observed. Wrinkles which are faults in flat-lying constitute also a defect in polycarbonate sheets (Pinner & Simpson, 2003).

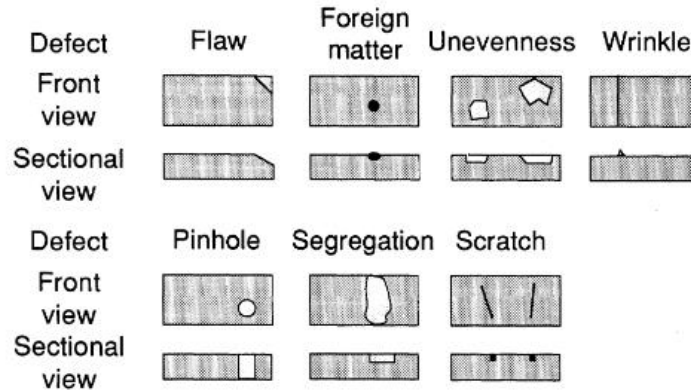


Figure 11 - Graphic models of front and sectional views of typical surface defects. Source: (Pinner & Simpson, 2003).

1.6.2. Detection and Identification of Surface Defects

Defects, as seen in chapter 1.6.1, must be detected and identified to ensure consistent product quality. Fast development of sophisticated computer systems, have ensured that the area of automatic sheet inspection has become progressively more important. All types of continuous sheet based plastics production processes can be inspected automatically. Detection of the defects can be recognized by many different methods. The selected method(s) depends largely on the purpose and the nature of the production to be employed. Those methods are based on obtaining signals from the surface and from a defect with different sensors. Transmission or reflection of radiation, electromagnetic or ultrasonic waves, are recorded so that comparison is made with data for satisfactory surfaces. One of the methods available is laser sensing, being very sensitive, it can detect defects down to 250-300 microns on a four-metre web (sheet with four-meter-wide), or 100 microns on a one metre web. The laser scans the surface and detection occurs because in a defect the intensity of light transmitted or reflected is different from a normal spot. Variations in reflection can indicate unevenness of surface, and, in a transmission system, differences in the transmission of light may indicate pinholes or foreign matter in sheets (Hudson, 1995). Figure 12 illustrates the laser sensing process for detection of defects in a sheet manufacturing industry.

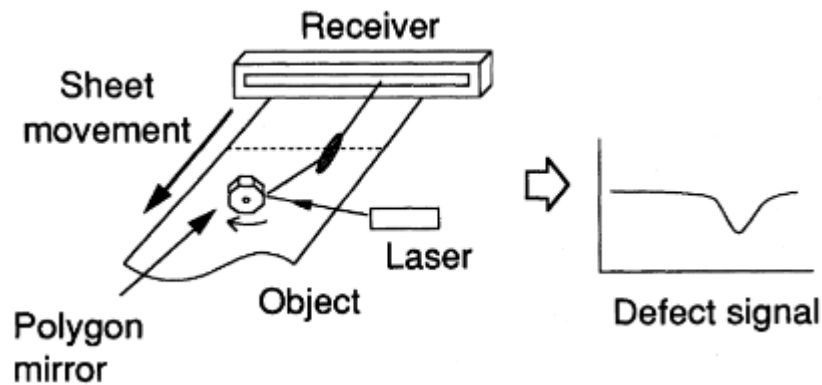


Figure 12 - Sensing with laser scanning (reflection systems). Source: (Hudson, 1995)

Another method is the ultrasonic sensing and, as the laser sensing method, it recognizes the variations on the reflected ultrasonic waves. Transmission of ultrasonic waves is difficult in air, one way to overcome this, is to examine the material immersed in water (Hudson, 1995). Figure 13 shows this process.

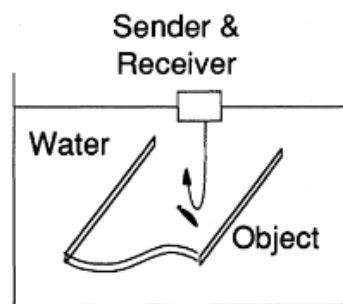


Figure 13 - Using an ultrasonic sensor (reflection system). Source: (Hudson, 1995)

Image sensing technology is based on sensing by two-dimensional photo systems. The information from the sheet under study is converted into electrical signals and then the resulting image is recognized and judged in a data processing unit. This method is used to automate visual inspection, saving labour and frees employees from necessary periods of intense concentration and prevents human error (Hudson, 1995).

As is mentioned before the choice of which systems to use depends on the application and what is required. Table 3 provides a comparison between the different recognition methods (Pinner & Simpson, 2003).

Table 3 - Defect recognition methods comparison. Adapted from: (Pinner & Simpson, 2003).

Requirement	Methods and assessment			
	Photo-sensor		Laser Beam scanning	Ultrasonic sensor
	One-dimensional	Two-dimensional		
Resolution	medium	Medium to small	large	Small*
Flexibility	medium	large	small	Small
Size of system	Small	Small	Large	large
Speed	Medium	Low	Fast	low
Application to samples	medium	wide	narrow	narrow

*Minimum 1mm.

1.6.3. Troubleshooting Approaches

In polycarbonate sheet production, there are many factors that affect not only the productivity of the process but also the final quality of the products. Different grades may have different processing conditions. It is important to focus on the root causes of defects to identify and solve the problem that occurs during processing. Observation is very important to solve any problem. The problems are interconnected between the process and end products. Troubleshooting is an effort that trusts in science and technology to eliminate the problems and improve quality with the goal to increase the process efficiency with quality of the end production (Subramanian, 2011).

The proper approach is important in eliminating process problems. Defects on the final product usually result from problems in one, or more, of three operation's areas; the premolding (material handling and storage); molding (conditions in the molding cycle) and postmolding (parts handling and finishing operations). Sawdust, contamination or defects involving colour, collection, painting and vacuum metallizing are due to deficiencies in the premolding or postmolding. Solutions for those areas can vary from being obvious or specialized.

Faults in the polycarbonate production process itself are related to the molding cycle, and can be attributed to the machines, molds, operating conditions, material, product design and management. Molding cycle problem analysis is concerned with three major elements in the molding operation: the injection molding machine (per example the injection flow); the mold (if everything is functioning properly) and the material (plastic formulations). The three variables that influence those three operation elements the most, are time, pressure and temperature (Noriega & Rauwendaal, 2001).

Before correcting a fault, one must find it, to do so, a good quality control is necessary, as referred in the last section (1.6.2). Also, maintenance of the machinery is very important, all equipment must be ready and available. Most molding problems are solved by varying machine conditions and changing mold conditions. However, if the problem persists, the cause and possible solution may be found by examining plastic variables as flow characteristics, melt viscosity at molding temperature and change in viscosity at different flow rates, thermal properties, heat distortion, specific heat, heat of fusion, thermal conductivity, and crystallites start to form, granulation size and shape and granulation lubrication. According to Rosato *et al.* (2001) it is important to have: a check list of how to solve a problem, such as narrow down the problem to a particular area, that is, machine, mold, operating conditions, material, product design, or management; a plan; watch molding conditions; change one condition at a time; allow sufficient time at each change; keep an accurate log of each change; check housekeeping (Rosato *et al.*, 2001).

1.7. Quality Assurance

Quality assurance can be achieved by implementing quality management systems, which can assist organizations in enhancing customer satisfaction. Customers require products with characteristics that satisfy their needs and expectations, which are expressed in product specifications and collectively referred to as customer requirements. The company should only produce products to their best capability without variance in quality, and final product's quality should meet what costumers requires, and not what they will accept. Customer requirements may be specified contractually by the customer or may be determined by the organization itself. In any case, the customer determines the acceptability of the product and because customer needs and expectations change, and also due to competitive pressures and technical advances, organizations are driven to improve continually their products and processes. Costumer quality requirements must not vary within the organization. Every product to be sell to the costumer is important and is manufactured using the same methods as any other product. When quality procedures are written, all jobs should require the same degree of supplier quality with a well-established and managed system place. One of the implications is that some jobs may have tighter specifications and they should be meeting on a daily basis schedule. (International for Standardization Organization, 2002 & Jr., 2010).

The quality assurance is secured by using a quality management system, that usually follows the requirements proposed by the ISO 9001:2015 standard (Strong, 2008; CERCO Working Group on Quality, 2000). A quality management system is based on quality management principles (QMP), which are a set of fundamental beliefs, rules and values that can be used as a foundation to guide an organization's performance improvement. They were developed and updated by international experts of the Quality Management & Quality Assurance (ISO/TC 176), which is responsible for developing and maintaining International Organization for Standardization's quality management standards. The seven quality management principles are costumer focus (meet customer requirements and to attempt to exceed customer expectations), leadership (establish unity of purpose and direction and create conditions in which people are

focused in achieving the organization's quality objectives), engagement of people (engaged people at all levels throughout the organization are essential to enhance its competence to create and deliver value), process approach (understanding how results are produced by this system allows an organization to optimize its performance), improvement (essential for an organization to maintain current levels of performance, to react to changes in its internal and external conditions and to create new opportunities), evidence-based decision making (decisions based on the analysis and evaluation of data and information are more probable to produce desired results) and relationship management (sustained success is more probable to be reached when the organization manages relationships with all its interested parties to boost their impact on its performance) (International Organization for Standardization, 2015; Hoyle, 2001).

1.7.1. System Guarantee Marks (Certification)

The ISO 9000 (family of quality management system standards) distinguishes between requests for quality management systems and requirements for products. Requirements for quality management systems are stated in ISO 9001, they are generic and applicable to organizations in any industry or economic sector regardless of the offered product category, although the ISO 9001 itself does not establish specifications for products (International for Standardization Organization, 2002).

2. FUNCTIONAL FORMS PLANT MASS BALANCE

2.1. Mass Balance Tool

As SABIC is changing its informatics system, a tool to calculate the Functional Forms plant line's production per batch was needed.

The first step to create that tool was to prepare a production process sketch. Raw materials, coming from the silos, enter the extruder and are melted and mixed getting out as continuous sheet. That sheet goes by a set of rolls, which confer the final thickness, getting into the masking station, where a polyethylene protection tape, called masking, is applied. After that, it is necessary to cut the continuous sheet into various sheets with the desired length and sometimes, also trim it. Those sheets are removed from the line by the stacking system and go to storage. Those production streams are represented in Figure 14.

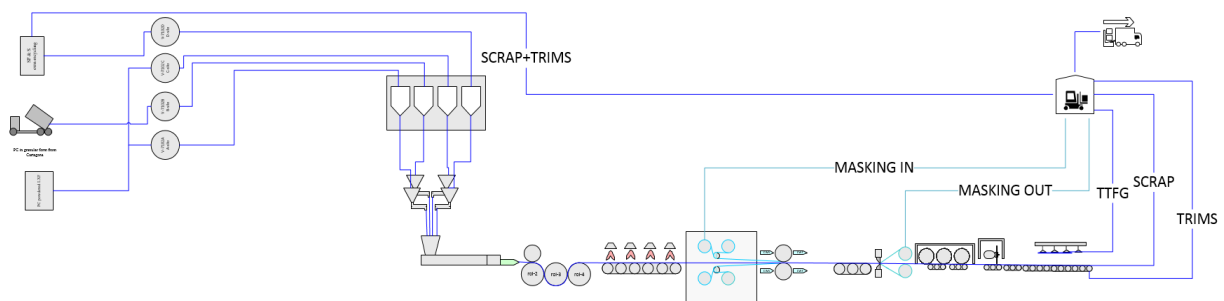


Figure 14 - Functional Forms production.

The first batch begins with the production of scrap until the desired parameters are reached and the final good product (TTFG) starts to be produced. The production schedule diagram is represented in Figure 15.

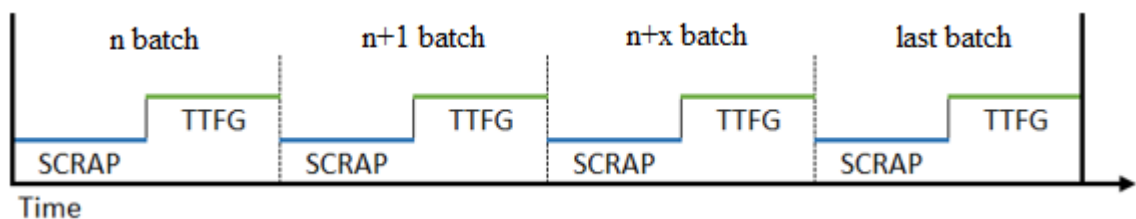


Figure 15 - Production schedule diagram.

Since the desired tool would work per batch, it was necessary to define what is a batch, and the scope of the mass balance. Although the production process starts in the silos the batch only starts when the operator presses “start” in the computer, which is located near the rollers, as showed in Figure 16. This means, that, the batch first gram is accounted just after the die, because this material is going to be the first shit. The last second and last gram is accounted

when the last sheet is stacked. Then if the next batch has different specs from the batch which is being produced, the material left in the line would be accounted as next batch's scrap.

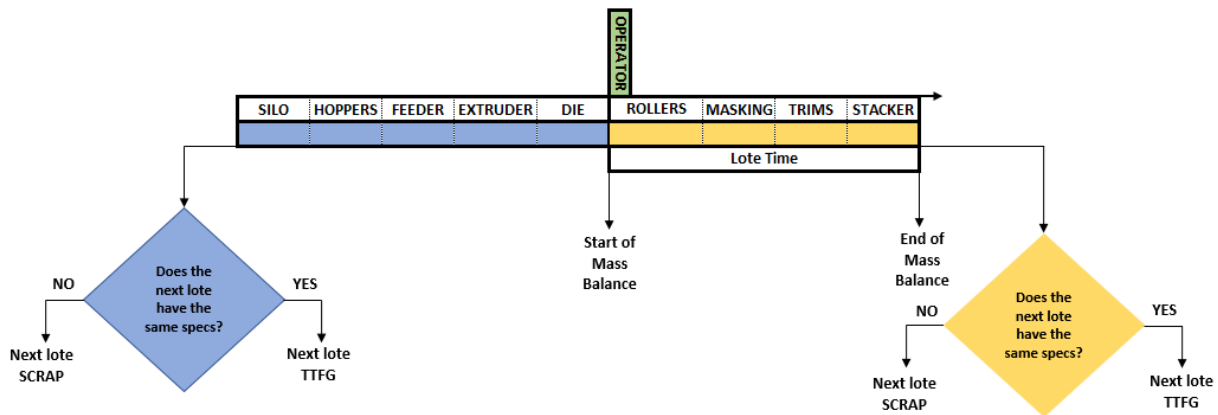


Figure 16 - Mass balance scope diagram over time.

Posteriorly an enquiry was made to study how the data was collected, where and how. To answer those questions, it was necessary to gather and combine the knowledge and experience of the process engineers, operators, information technology department and sales department, as well.

The calculation tool must be easy to use, simulate the reality as much as possible, be applicable to all the six lines and must have a maximum 2% error per batch.

It was determined there were two ways to elaborate the tool. One with the input based on the quantities given by the hoppers, and the outputs based on the dimensions and percentages. The other, with the same input, has an output determined on the line speed and batch run time. As in the first method is based on theoretical dimensions and percentages, it was decided to follow the second one and adjust it to the reality as much as possible.

Follows the chosen method:

2.1.1. Mass Balance Tool Calculation

2.1.1.1. Raw Material Usage

The sum of the raw material provided by each of the seven feeders (F_A , F_B , F_C , F_D , F_E , F_F , F_G), gives the total raw material.

$$F_A + F_B + F_C + F_D + F_E + F_F + F_G = \text{total raw material (kg)} \quad (1)$$

2.1.1.2. Co-Extruder

In some batches raw material is also injected from the co-extruder. That amount of raw material is given by:

$$co\ extruder\ (rpm) \times Line\ \left(\frac{kg}{rpm}\right) = total\ co\ extruder\ (kg) \quad (2)$$

2.1.1.3. Masking In

Masking can be applied on the top and bottom of the sheet, its width and thickness depend on the masking type applied.

Masking applied on the top of the sheet is given by:

$$\begin{aligned} & masking\ width\ (m) \times masking\ top\ thickness\ (m) \times line\ speed\ \left(\frac{m}{min}\right) \\ & \times masking\ density\ \left(\frac{kg}{m^3}\right) \times masking\ time\ (min) \\ & = masking\ top\ (kg) \end{aligned} \quad (3)$$

Masking applied on the bottom of the sheet is given by:

$$\begin{aligned} & masking\ width\ (m) \times masking\ bottom\ thickness\ (m) \times line\ speed\ \left(\frac{m}{min}\right) \\ & \times masking\ density\ \left(\frac{kg}{m^3}\right) \times masking\ time\ (min) \\ & = masking\ bottom\ (kg) \end{aligned} \quad (4)$$

The total masking applied per batch is given by the sum of the previous equations:

$$masking\ Top\ (kg) + masking\ bottom\ (kg) = total\ masking\ (kg) \quad (5)$$

2.1.1.4. TTFG

The total TTFG per batch is calculated based on time, line speed and its dimensions:

$$production\ Time\ (min) - scrap\ Time\ (min) = TTFG\ time\ (min) \quad (6)$$

$$line\ speed\ \left(\frac{m}{min}\right) \times TTFG\ time\ (min) = TTFG\ Length\ (m) \quad (7)$$

$$TTFG \text{ length (m)} \times TTFG \text{ density } \left(\frac{kg}{m^3} \right) \times TTFG \text{ width (m)} \times TTFG \text{ thickness (m)} = \text{total TTFG (kg)} \quad (8)$$

2.1.1.5. Scrap

As the TTFG, the amount of scrap is calculated based on scrap time and line speed. To ease the calculations, it was considered that TTFG density and thickness are the same as the scap's:

$$\text{scrap time (min)} \times \text{line speed } \left(\frac{m}{min} \right) = \text{scrap length (m)} \quad (9)$$

$$\text{scrap length (m)} \times TTFG \text{ density } \left(\frac{kg}{m^3} \right) \times TTFG \text{ thickness (m)} \times \text{scrap width (m)} = \text{scrap (kg)} \quad (10)$$

$$\text{scrap (kg)} + \text{masking scrap (kg)} = \text{total scrap (kg)} \quad (11)$$

2.1.1.6. Trims

Trims are considered the difference between the full web and TTFG. It was considered that there isn't sawdust on TTFG, being only on the trims:

$$\text{web width (m)} - TTFG \text{ width} = \text{trims width (m)} \quad (12)$$

$$TTFG \text{ length (m)} \times TTFG \text{ density } \left(\frac{kg}{m^3} \right) \times TTFG \text{ thickness (m)} \times \text{trims width (m)} = \text{trims (kg)} \quad (13)$$

$$\text{trims (kg)} + \text{masking trims (kg)} = \text{trims with masking and sawdust (kg)} \quad (14)$$

$$\text{trims with sawdust (kg)} - \text{total sawdust (kg)} = \text{total trims (kg)} \quad (15)$$

2.1.1.7. Masking

The masking is calculated as in the inputs, but using the masking application time and the masking TTFG time is possible to know how much masking is used in TTFG, trims and scrap:

$$\begin{aligned} & \text{masking total time (min)} - \text{masking TTFG time (min)} \\ & = \text{masking scrap time} \end{aligned} \quad (16)$$

$$\begin{aligned} & \text{masking width (m)} \times \text{masking top thickness (m)} \times \text{line speed} \left(\frac{\text{m}}{\text{min}} \right) \\ & \times \text{masking density} \left(\frac{\text{kg}}{\text{m}^3} \right) \times \text{masking TTFG time (min)} \\ & = \text{masking TTFG Top (kg)} \end{aligned} \quad (17)$$

$$\begin{aligned} & \text{TTFG width (m)} \times \text{masking bottom thickness (m)} \times \text{line speed} \left(\frac{\text{m}}{\text{min}} \right) \\ & \times \text{Masking density} \left(\frac{\text{kg}}{\text{m}^3} \right) \times \text{masking TTFG time (min)} \\ & = \text{masking TTFG bottom (kg)} \end{aligned} \quad (18)$$

$$\begin{aligned} & \text{TTFG masking top (kg)} + \text{TTFG masking bottom (kg)} \\ & = \text{yotal TTFG masking (kg)} \end{aligned} \quad (19)$$

$$\begin{aligned} & \text{trims width (m)} \times \text{masking top thickness (m)} \times \text{line speed} \left(\frac{\text{m}}{\text{min}} \right) \\ & \times \text{masking density} \left(\frac{\text{kg}}{\text{m}^3} \right) \times \text{masking TTFG time (min)} \\ & = \text{masking trims top (kg)} \end{aligned} \quad (20)$$

$$\begin{aligned} & \text{trims width (m)} \times \text{masking bottom thickness (m)} \times \text{line speed} \left(\frac{\text{m}}{\text{min}} \right) \\ & \times \text{masking density} \left(\frac{\text{kg}}{\text{m}^3} \right) \times \text{masking TTFG time (min)} \\ & = \text{masking trims bottom (kg)} \end{aligned} \quad (21)$$

$$\begin{aligned} & \text{tims masking top (kg)} + \text{trims masking bottom (kg)} \\ & = \text{total trims masking (kg)} \end{aligned} \quad (22)$$

$$\begin{aligned} & \text{web width (m)} \times \text{masking top thickness (m)} \times \text{line speed} \left(\frac{\text{m}}{\text{min}} \right) \\ & \times \text{masking density} \left(\frac{\text{kg}}{\text{m}^3} \right) \times \text{masking Scrap time (min)} \\ & = \text{masking scrap top (kg)} \end{aligned} \quad (23)$$

$$\begin{aligned}
 & \text{web width (m)} \times \text{mbottom thickness (m)} \times \text{line speed } \left(\frac{\text{m}}{\text{min}} \right) \\
 & \times \text{masking density } \left(\frac{\text{kg}}{\text{m}^3} \right) \times \text{masking scrap time (min)} \\
 & = \text{masking scrap bottom (kg)}
 \end{aligned} \tag{24}$$

$$\begin{aligned}
 & \text{scrap masking top (kg)} + \text{scrap masking bottom (kg)} \\
 & = \text{total masking scrap (kg)}
 \end{aligned} \tag{25}$$

2.1.1.8. Sawdust

To facilitate the calculations, it was assumed the sawdust production was 0.004m per saw used:

$$\begin{aligned}
 & (n^{\circ} \text{saws} \times 0.004 \text{ m}) \times \text{TTFG length (m)} \times \text{TTFG density } \left(\frac{\text{kg}}{\text{m}^3} \right) \\
 & \times \text{TTFG thickness (m)} = \text{total sawdust (kg)}
 \end{aligned} \tag{26}$$

2.1.1.9. Input

The total input is given by:

$$\begin{aligned}
 & \text{total raw material (kg)} + \text{total coextruder (kg)} + \text{total masking (kg)} \\
 & = \text{total input (kg)}
 \end{aligned} \tag{27}$$

2.1.1.10. Output

The total output is given by:

$$\begin{aligned}
 & \text{total TTFG (kg)} + \text{total scrap (kg)} + \text{total trims (kg)} + \text{total sawdust (kg)} \\
 & = \text{total output (kg)}
 \end{aligned} \tag{28}$$

2.1.1.11. Error

The error of the balance is given by:

$$\frac{|\text{total output (kg)} - \text{total input (kg)}|}{\text{total output (kg)}} \times 100 = \% \text{ error} \tag{29}$$

2.2. Mass Balance Tool Model Concept

This tool was created in Microsoft® Excel, and after all the inputs are filled it is possible to calculate all the production flows compatible with all lines. To do that, it was necessary to gather a database of all the raw materials used, masking types, grades, colours and some production specifications. Its final appearance is presented in the next sub chapters.

2.2.1. Necessary Inputs per Batch

The necessary inputs per batch must be filled in after the batch is produced. The objective is that, in the future, some of the cells would be automatically filled. Those are represented in Table 4.

Table 4 - Inputs (light orange cells) which must to be filled in by the operator.

Manual Input Operator:			
Line			
Process Order			
Batch number			
Grade			
Colour			
Masking TOP			
Masking BOTTOM			
Gauge			mm
Number of Trim saws			saws
Feeders	Total Raw Material Usage		kg
A	(NONE)		%
B	(NONE)		%
C	(NONE)		%
D	(NONE)		%
E	(NONE)		%
F	(NONE)		%
G	(NONE)		%
Co-Extruder			
Velocity			rpm
Web			
Width			mm
TTFG			
Width			mm
Length			mm
Number of sheets			units
Scrap Loss			
Scrap			kg

2.2.2. Input calculations

With the previous data, and using the equations previously established, it was possible to quantify the total input, as well as the percentage of masking (top and bottom) and raw material used.

Table 5 - Total input calculation section.

Raw Material Usage							
Feeder	Raw Material	Weight (kg)					
A	A	8 550,00					
B	(NONE)	0,00					
C	C	950,00					
D	(NONE)	0,00					
E	(NONE)	0,00					
F	(NONE)	0,00					
G	(NONE)	0,00					
		TOTAL	9500,000				
				Raw Material Total			
				9 500,00	kg		
Co-Extruder Usage							
Co-Extruder (rpm)	Line (kg/rpm)			Co-Extruder Total Usage			
0,000	0,5636			0,000	kg		
Masking Usage							
TOP	Masking Length (m)	Density (kg/m³)	Thickness (m)	Width (m)	Masking Top (kg)		
	780,000	967,1429	7,00E-05	1,270	67,064		
				Masking Usage Total			
BOTTOM	Masking Length (m)	Density (kg/m³)	Thickness (m)	Width (m)	Masking Top (kg)	134,13	kg
	780,000	967,143	7,00E-05	1,270	67,064		
					Total Input	9 634,13	kg

2.2.3. Output Calculations

Also using the data, provided by the operator, it is also possible to quantify the total output as the percentage of TTFG, trims, sawdust and masking (top and bottom).

Table 6 - Total Output calculation.

Masking		
Masking Total (kg)	Masking TTFG (kg)	Masking Trims (kg)
134,127	130,959	3,168

Trims Loss			
Trims with sawdust (kg)	Masking Trims (kg)	Total Trims with Sawdust (kg)	Total Masking Without Sawdust (kg)
1316,952	3,168	1320,120	1269,951

Trims Loss Total	
1 269,95	kg

Scrap Loss	
Scrap (kg)	
500,000	

Scrap Loss Total	
500,00	kg

TTFG					
Width (m)	Length (m)	Density (kg/m³)	Thickness (m)	TTFG (kg)	Total TTFG (kg)
1,24	780,000	1340,00	6,00E-03	7776,288	7907,247

TTFG Total	
7 907,25	kg

Sawdust		
n of saws	sawdust width (m)	Sawdust (kg)
2	0,008	50,170

Sawdust (kg)	
50,17	kg

Total Output	9 727,37	kg
	0,97%	Error

2.2.4. Final Output

In the end, comparing the results from the input with the output it is possible to determine the error between both.

Table 7 - Mass balance final output.

INPUT				OUTPUT		
Raw Material Usage	9 500,00	98,6%	98,61%	TTFG + Masking	7 907,25	81,3%
Co-extruder Usage	0,00	0,0%		Scrap Masking	Loss + 500,00	5,1%
Masking Usage	134,13	1,4%	1,39%	Trims Masking	Loss + 1 269,95	13,1%
				Sawdust	50,17	0,5%
Total	9 634,13	100,00%	100,00%	Total	9 727,37	100,00%
				Error	0,97%	

2.2.5. Mass Balance Calculation Tool Final Concept

After many versions and tests with past batches of all lines, the final concept of the mass balance calculation was achieved and is presented in Figure 17. It is the junction of the Table 4, Table 5, Table 6 and Table 7, however due to the tool's large size, it is not possible to display the full extension, with a high quality image, in this document.

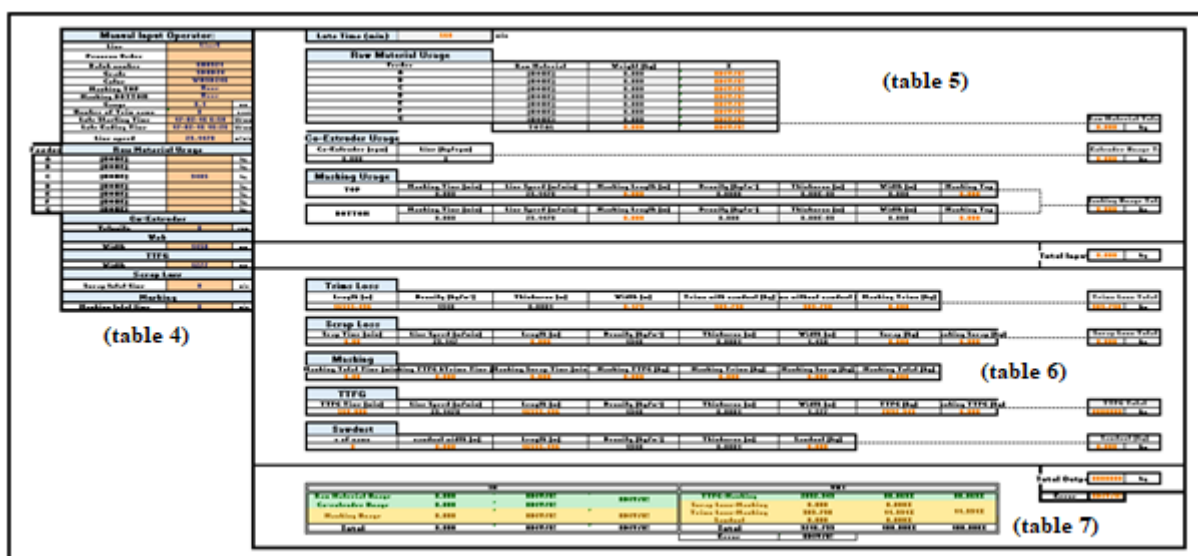


Figure 17 - Mass balance calculation tool final concept.

3. PRODUCTION AND WASTE ANALYSIS

3.1. Production Analysis

A mass balance of the plant was elaborated, considering all the 6 lines in 2014 and 2015. In the analysis it was considered the raw material usage, scrap, trims and final product (TTFG).

Following it is presented the mass balance of individualized production per line as well as the overall production of the entire plant for the years 2014 and 2015.

3.1.1. Line 1

Line 1 runs almost all year and only produces plastic sheet, having the possibility to trim them. The total production of 2015 was lower than in the previous year, but the percentage of final product (TTFG) was almost the same (Figure 18).

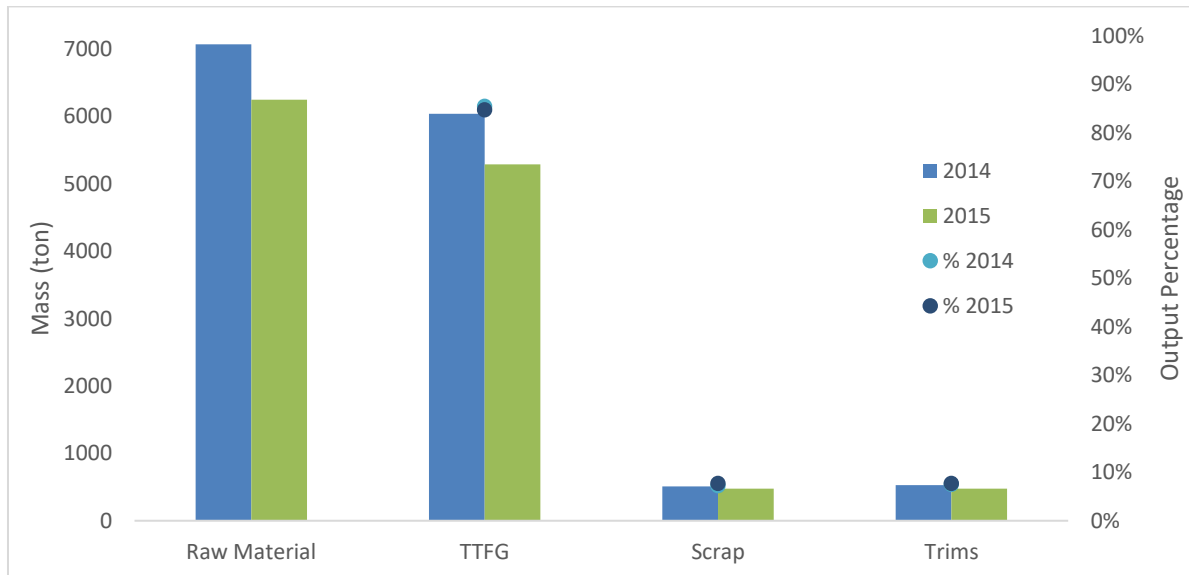


Figure 18 - Line 1 production in 2014 and 2015.

3.1.2. Line 2

The production of line 2 was similar for both years. This is represented in Figure 19.

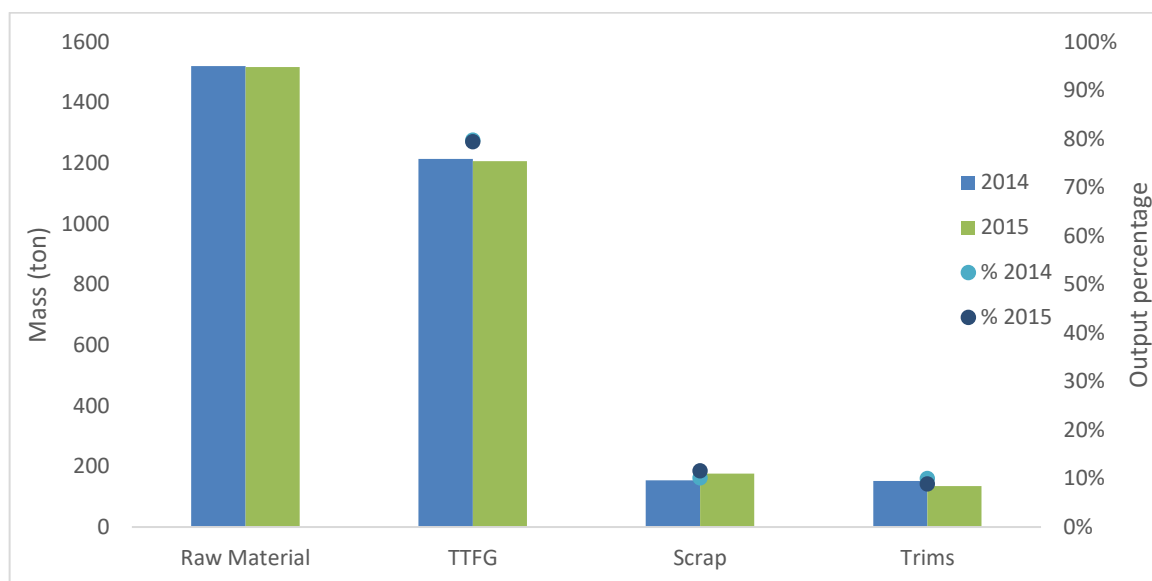


Figure 19 - Line 2 production in 2014 and 2015.

3.1.3. Line 3

Line 3 produced less in 2015 than in 2014, but the yield was a little bit higher (Figure 20).

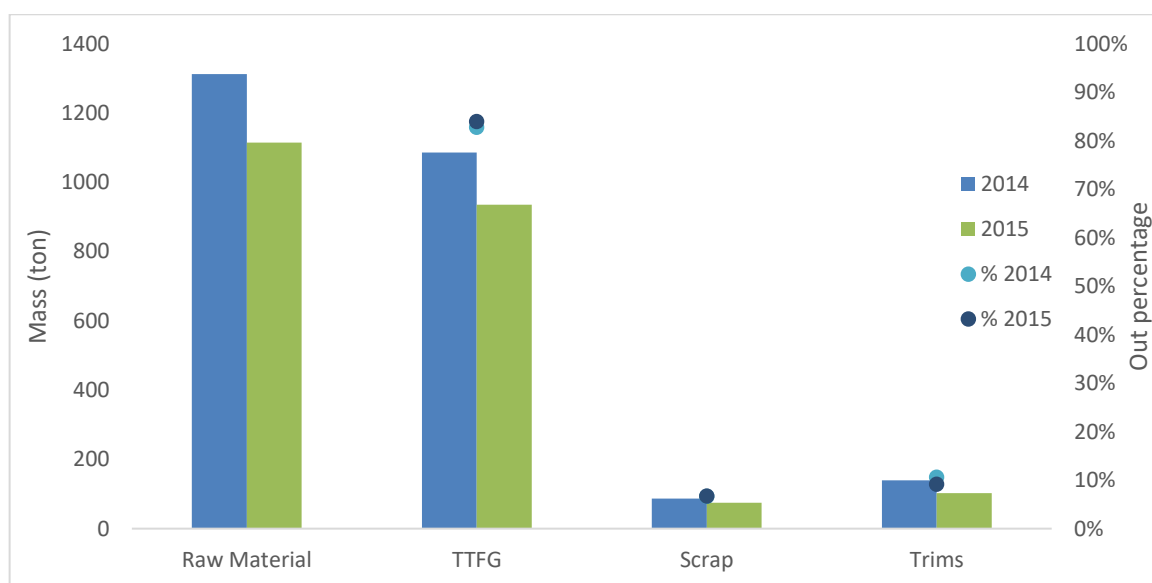


Figure 20 - Line 3 production in 2014 and 2015.

3.1.4. Line 4

Line 4 produces plastic sheet with optical quality, this line produced less in 2015, but with the same percentage of final product (Figure 21).

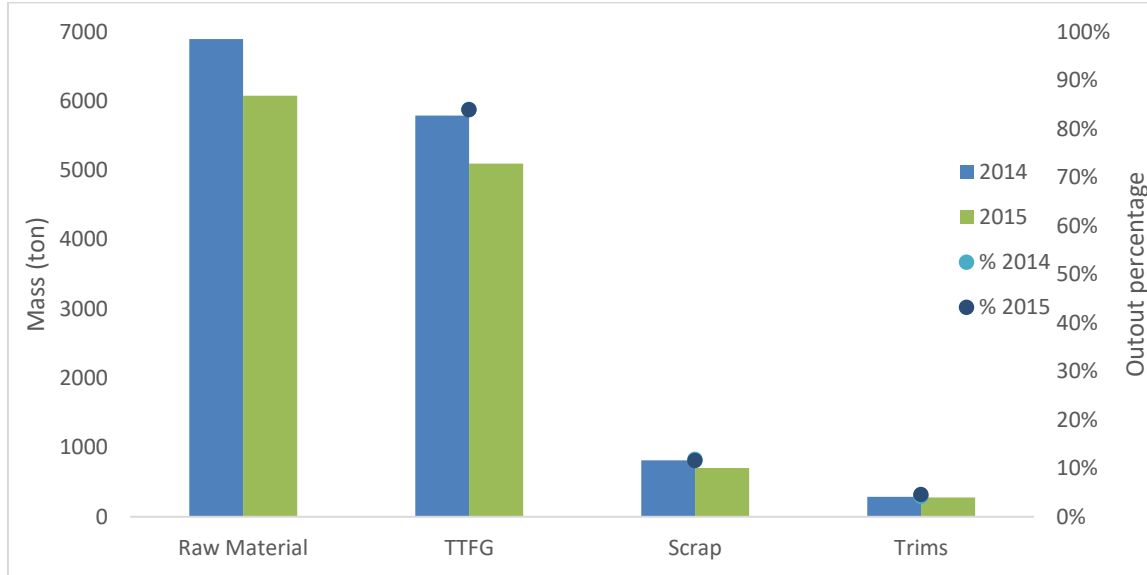


Figure 21 - Line 4 production in 2014 and 2015.

3.1.5. Line 5

Line 5 and Line 6 produce only plastic film. Line 5 produced less in 2015 with the same yield as in the previous year (Figure 22).

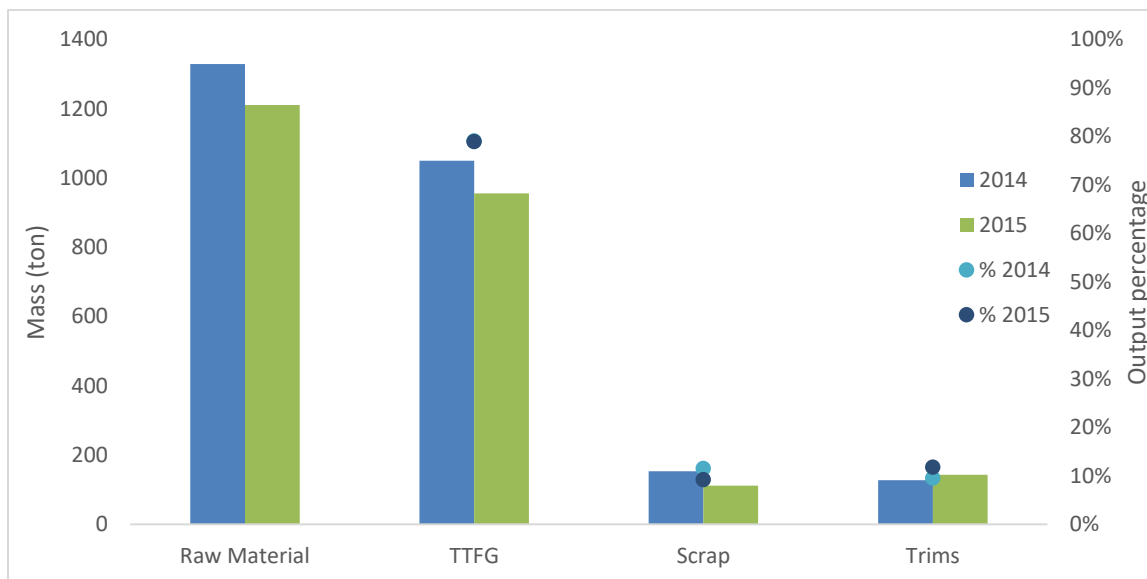


Figure 22 -Line 5 production in 2014 and 2015.

3.1.6. Line 6

Line 6 was the only line that produced more in 2015 than in 2014, but the percentage of final product dropped 0.6% (Figure 23).

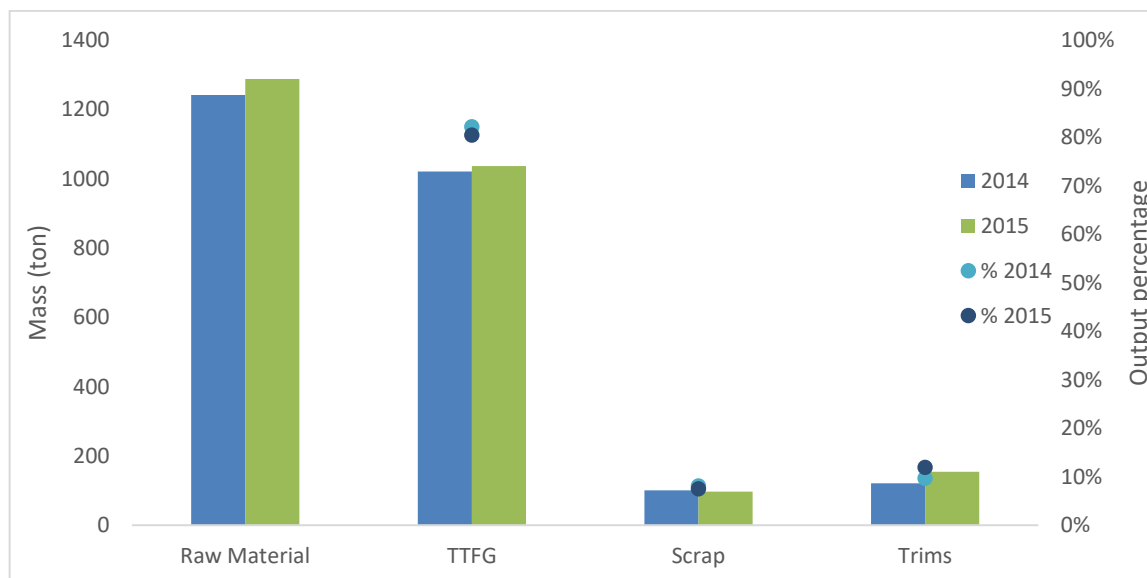


Figure 23 - Line 6 production in 2014 and 2015.

3.1.7. Functional Forms plant

The plant's total production dropped in 2015, being produced less TTFG and the yield dropped as well by 0.4% (Figure 24).

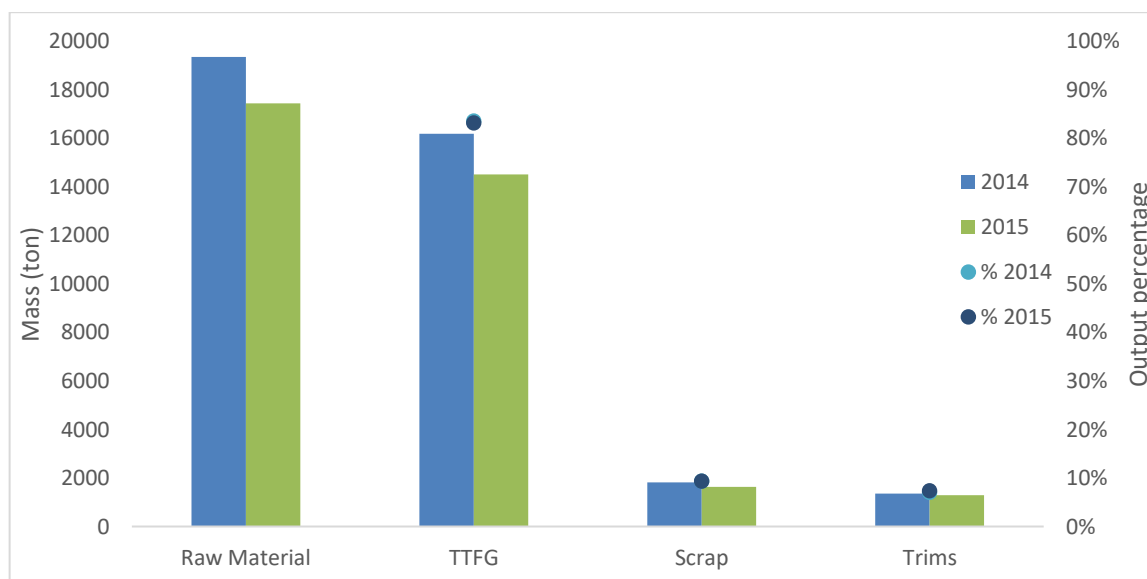


Figure 24 - Functional Forms plant production in 2014 and 2015.

Despite the percentage of the waste being small, it represents a large amount of material. Even though it is reusable, it has an additional cost. Thus, it was important to study possible measures to reduce the volume of waste generated, which is presented in the next section.

3.2. Wastes Analysis

Posteriorly to the mass balance of all production lines of the plant, another analysis has been prepared with focus on the scrap streams. The goal was to identify which are the biggest losses and set actions to reduce them. As the production analysis, this one also started to focus in each line.

The waste production is divided in six categories, changes, quality, start up, operational, failure and others. Changes comprehends all material wasted due to changes between batches until it reaches the desired parameter, like, for example, changes in the thickness of the produced sheet. The category quality, is relative to quality issues, such as non-conformity product. The material wasted when a run of new batch starts is quantified in the start up category. Operational is the material used in line's cleaning and maintenance. Failure is the material wasted due to a failure in the machinery. Finally, if the reason for the wasted material doesn't fit in the previous categories, it goes to category other.

3.2.1. Sheet Lines (Line 1, line 2, line 3 and line 4)

Analysing Figure 25 it is possible to conclude that line 1 is the main production sheet line of the plant (without optical quality), producing a wide range of grades, thicknesses, widths and colours. To produce that vast variety, it is necessary to apply a lot of changes between batches, being most of its wastes produced by that reason.

Line 2 is similar to line 1 but in a smaller production scale. The wasted material due to changes increased 4% from 2014 to 2015.

In line 3 not only the total wasted material reduced, but also there was a greater care to categorize the wasted material in 2015. Being in 2015 the reason for the most wasted material the changes, like in line 1 and 2.

There are three categories responsible for the most wasted material in line 4, those are operational, changes and quality. This line produces material of high optical quality, so is necessary to clean the line a lot more often (operational), and reach a certain amount of quality aspects, and take samples frequently (quality).

3 - Production and Wastes Analysis

SABIC's Functional Forms Plant Mass Balance, Production and Waste Analysis, and Sawdust Removal and Elimination Optimization

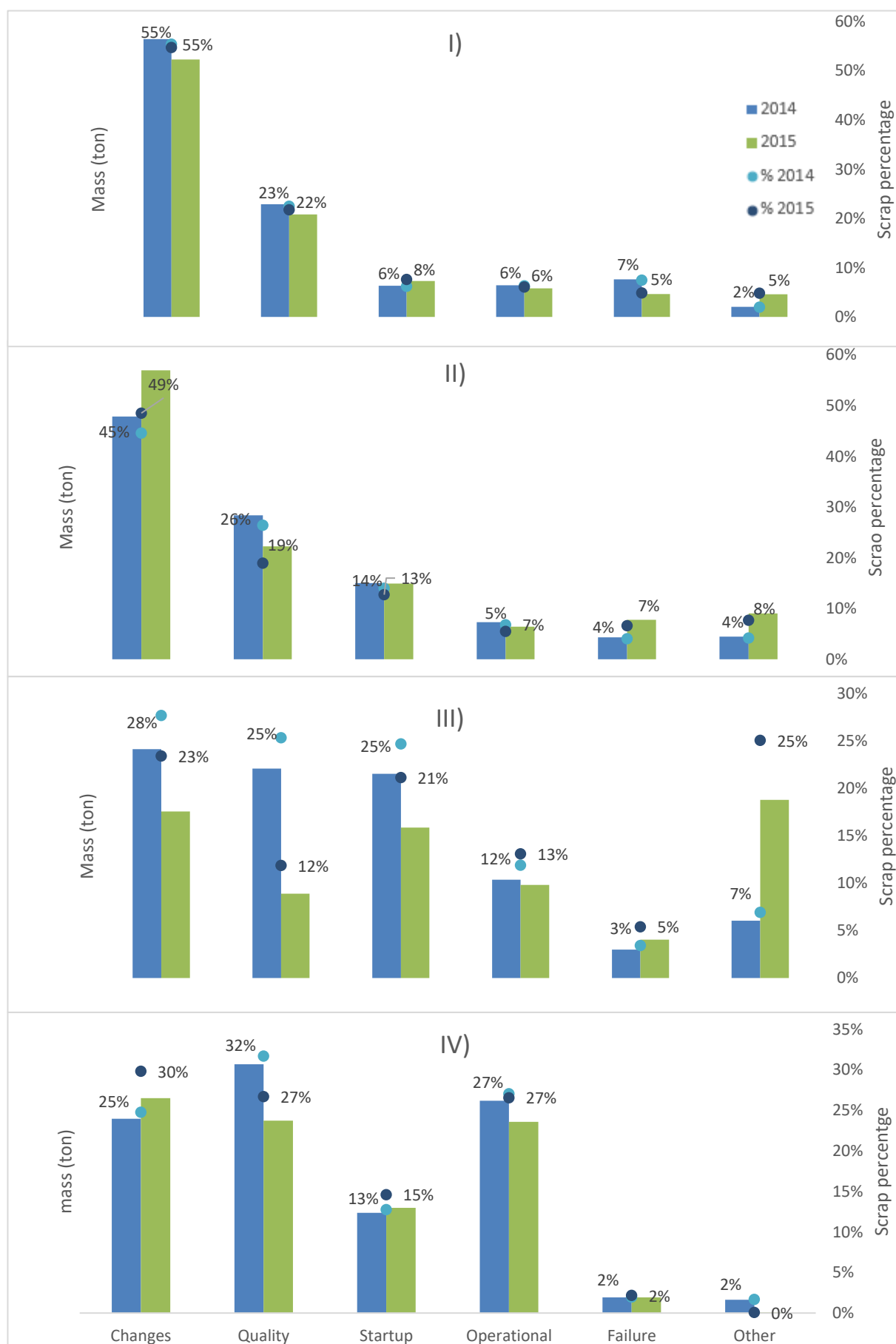


Figure 25 – Wastes produced by line 1 (I), Line 2 (II), Line 3 (III) and line 4 (IV) in 2014 and 2015.

3.2.2. Film lines (Line 5 and 6)

Line 5, as well as line 6, produces film. In 2015 less quantity of wasted material was produced. The three categories which produce the most, in both years, are the start up, changes and quality. This is shown in Figure 26.

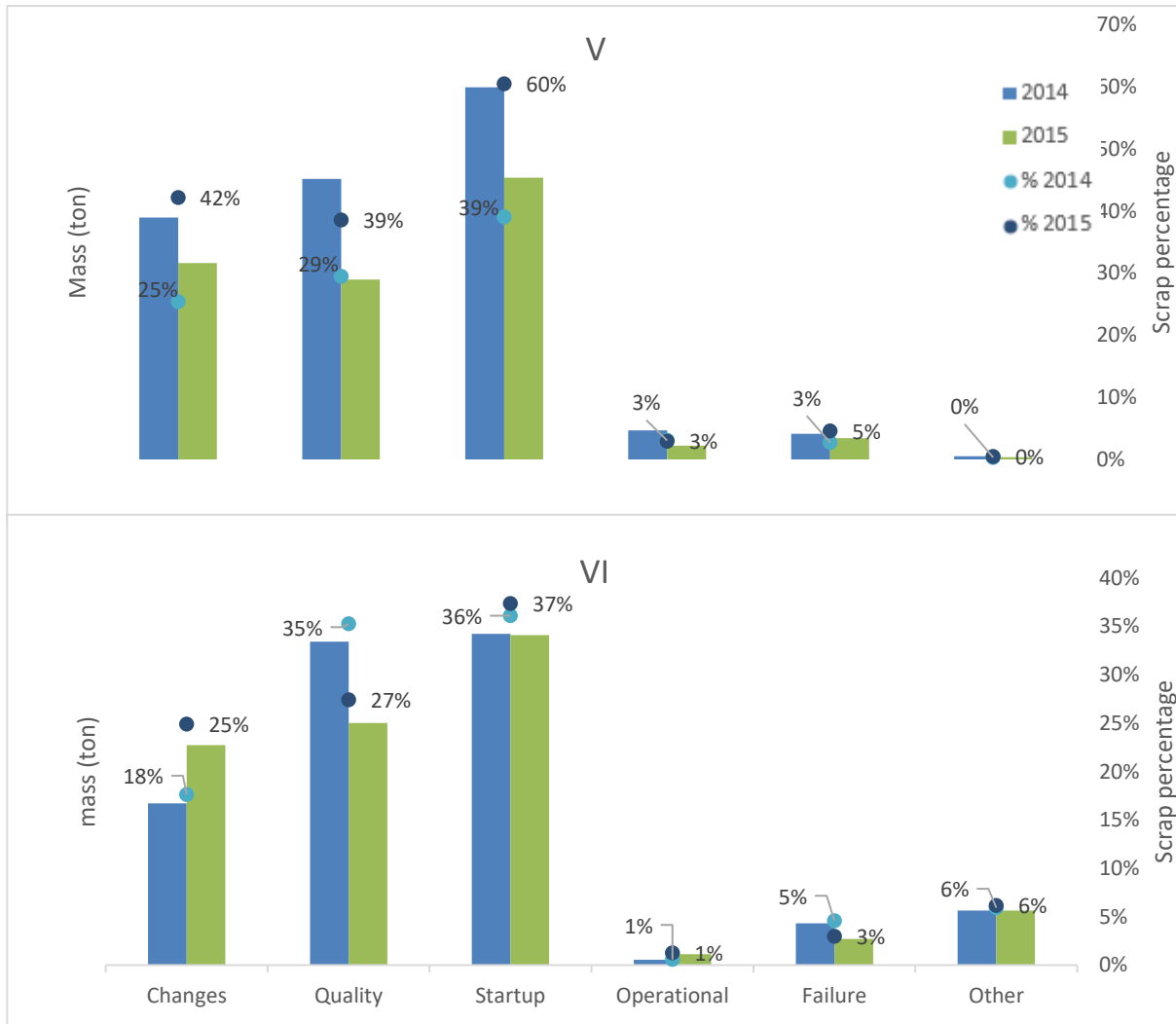


Figure 26 – Wastes produced by line 5 (V) and line 6 (VI) in 2014 and 2015.

3.2.3. Functional Forms plant

Between both years there was a reduction in the total wasted material produced. Also, Figure 27 shows that the percentages produced by each category almost didn't differ.

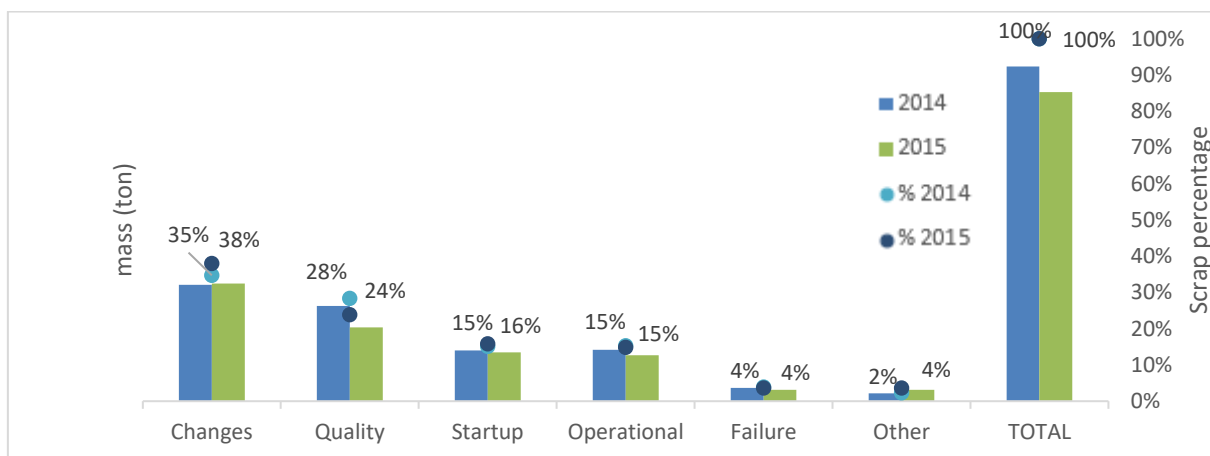


Figure 27 - Functional Forms plant wastes production in 2014 and 2015.

The graph of Figure 28 summarizes this analysis for all the lines, showing in which categories per percentage were produced per line in 2015. This visual representation allows to determine which areas have room to improve.

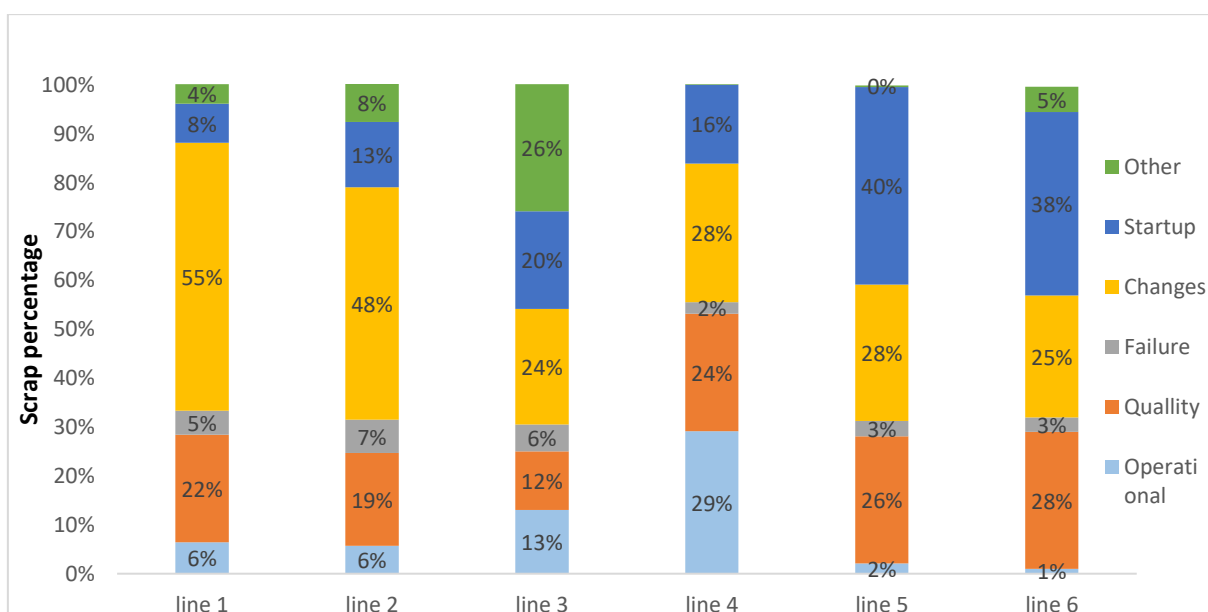


Figure 28 - Percentage of wastes category production per line in 2015.

Analysing Figure 28, it was determined that the focus to reduce the wastes produced should be the changes category for sheet lines, plus operational for line 4. Improvements in line 1 and 4 would have the biggest impact on total waste, since they are the ones that produce the most. Where is more room to improve on the film lines is the start up category. Therefore a deeper analysis of those determined categories followed.

Figure 29 represents the wasted material caused by changing colour, grade, masking or thickness between batches for line 1 (I), line 2 (II) and line 3 (III) in 2014 and 2015.

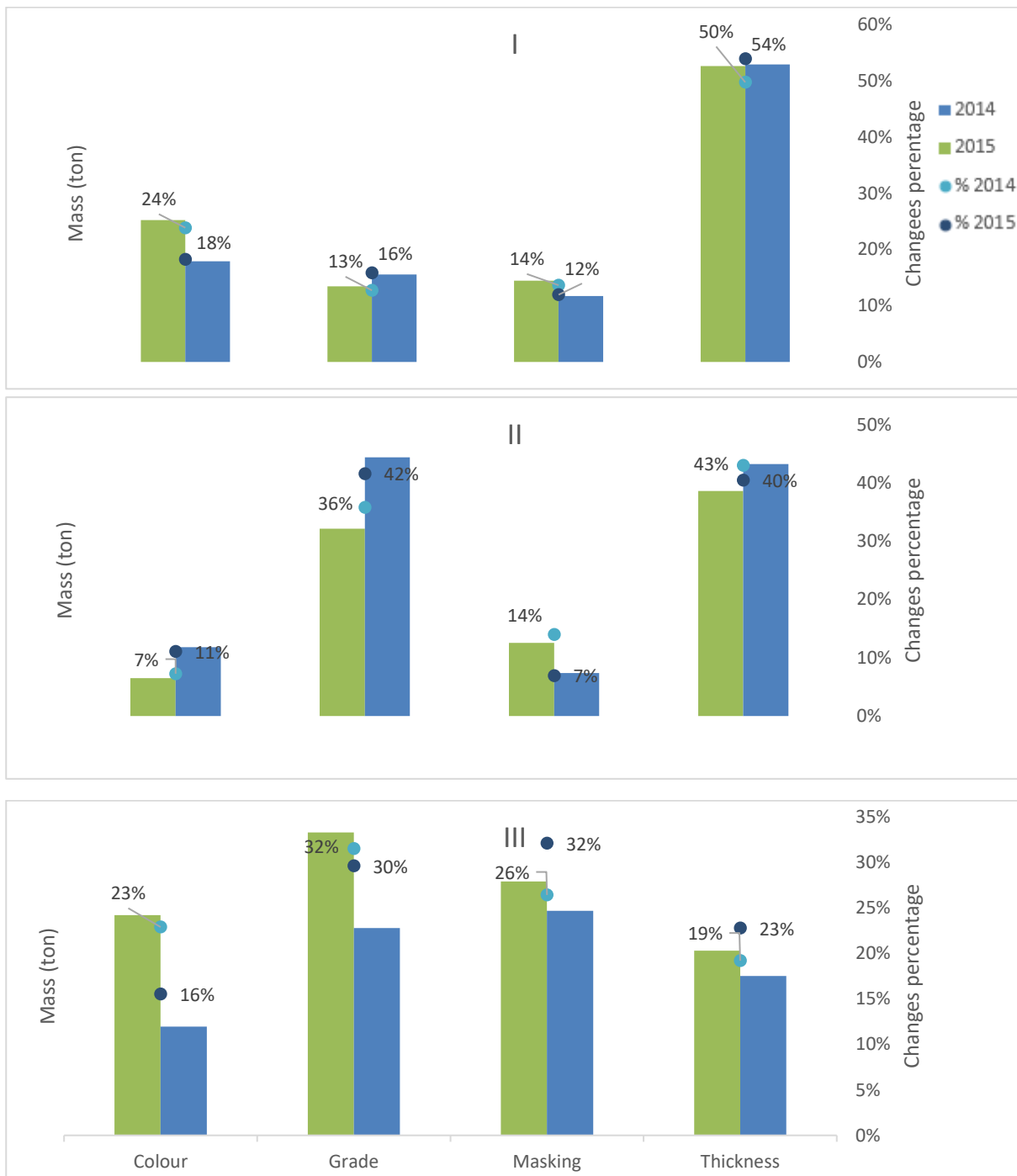


Figure 29 - Wastes produced in changes category in line 1 (I), 2 (II) and 3 (III) in 2014 and 2015.

During this analysis it was possible to verify that producing long runs helps in increase the yield and minimize the production wasted material. It was also determined that small changes in the thickness of the sheet produces less scrap than big jumps in the thickness. It was not possible to see a correlation between the quantity of scrap produced and some specification, like a specific colour or thickness. But in other hand, higher yields were achieved by the specifications which were produced in most quantity during the year. This shows that it is essential to develop

a production planning always with the intention of minimizing the changes between batches. Those conclusions were not exclusive for line 1, 2 and 3 but for all the six lines.

Figure 30 represents the wasted material produced caused by changing colour, grade, masking or thickness and roll cleaning (Operational) between batches for line 2 in 2014 and 2015. Besides the categories caused by changes in production, in Figure 30, there is also the roll cleaning, this is because it is the main cause of wasted material in this line, constituting almost all the operational category.

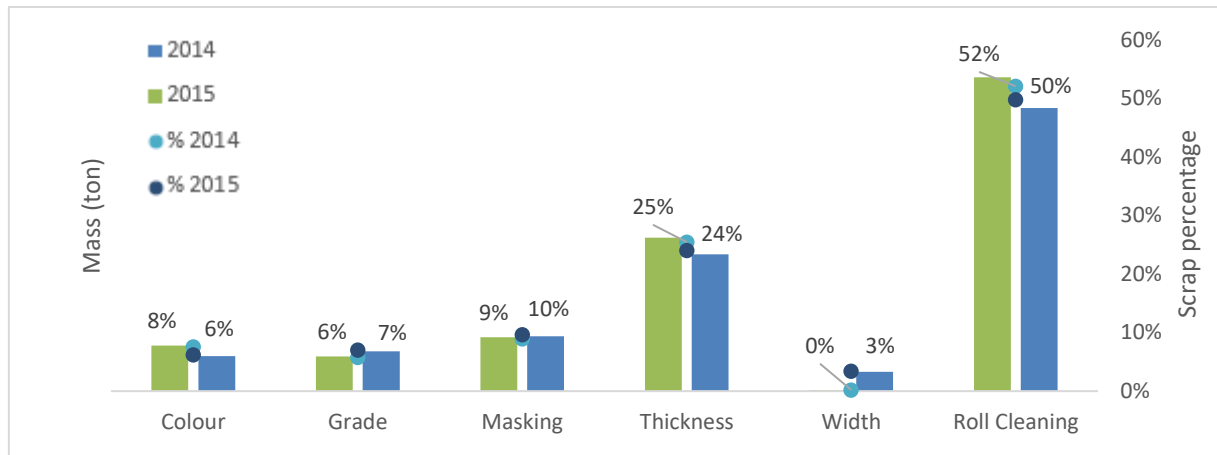


Figure 30 - Line 4 wastes production in changes category and in roll cleaning in 2014 and 2015.

Figure 31 represents the wasted material produced caused by starting the line 5 (V) and line 6 (VI) in 2014 and 2015.

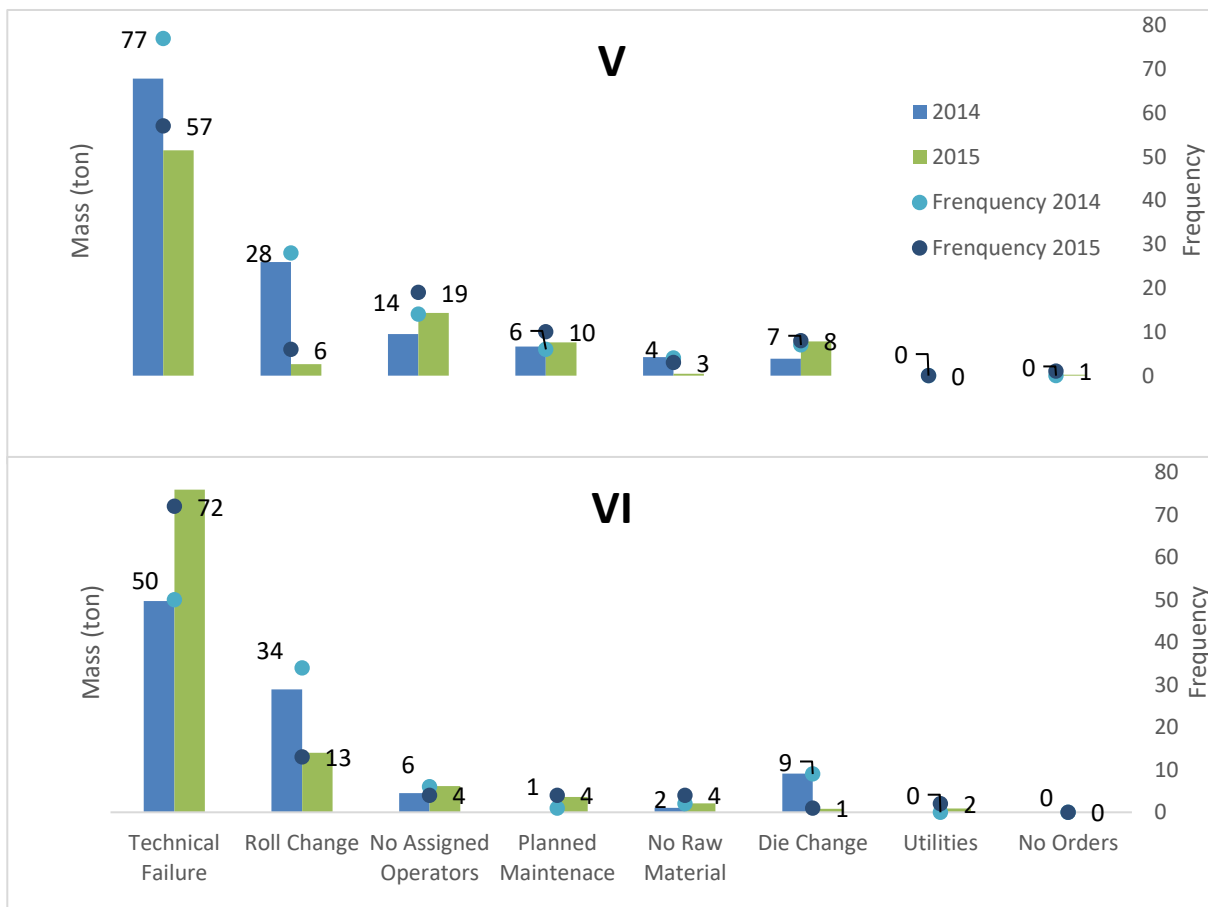


Figure 31 - Line 5 (V) and 6 (VI) wastes production in “changes” category in 2014 and 2015.

From Figure 31 is possible to see a direct correlation between the number of occurrences and the quantity of total scrap produced. Being the technical failure the principal cause for frequent start ups between batches.

3.3. Analysis follow up

Based on this analysis it was possible to observe that the total production and the total yield dropped in 2015. Line 1 and Line 4 are the ones which produce the most, having the biggest influence in the scrap production.

For the solid sheet lines, the biggest cause to scrap production are the changes in the middle of the production blocks, however for the film lines are the start-ups. Also, the trend is: the more you produce of each grade, colour or thickness the highest yield will be possible to achieve.

This analysis has shown that there is room for improvement and allowed to set the significant areas to focus on. Based in this analysis and its conclusions, a small team, involving both

manufacturing and sales departments, held a meeting in which it was possible to participate, to define some actions for the continuation of this project after the end of the internship

All Lines: Rationalization of certain colours

- Line 1: Optimize block scheduling;
- Line 1 and 2: Rationalization of certain widths;
- Line 1 – 4: Gathering detailed information according to thickness and colour changes;
- Line 1 – 4: Rationalization width 1250mm and above 5mm gauge;
- Line 4: Project Roll cleaning (already being developed);

4. SAWDUST REMOVAL AND ELIMINATION OPTIMIZATION

The presence of saw dust in the final product, originating from both online and off line, prevents SABIC to grow in the automotive glazing market.

The goal of this second project of the internship is to set some proposal actions to reduce the production of sawdust or separate it from the final product, meeting the costumer's expectations. The focus of this project is the line 4, the optical quality one.

The first approach was to enquire what were the process conditions as well as the line's conditions and configurations, to get feedback from people who directly or indirectly have knowledge about this problem. It was also studied and gathered the conclusions of past projects about this issue, got feedback from other sites around the world and from the company that coats the sheets after they are produced in the line.

4.1. Functional Forms Line 4

Line 4 is where the polycarbonate sheets with optical quality are produced, due to that it is necessary to have extra care. From the extruder until after the masking station, the line is isolated by a "greenhouse", to prevent contamination by dust and dirt particles. The "greenhouse" is also equipped with dehumidifiers, but it hasn't static electricity control. Although line 4 is protected, the sawing station isn't. The sawing station (Figure 32) isn't modern, being quite old and outdated. It is provided with a cross saw, which performs the perpendicular cuts, and two trim saws, which perform the parallel cuts.



Figure 32 - Sawing station of line 4.

The trim saws can run both at the same time, or not. They are installed on the top of the sheet and their cut depth cannot be adjustable. The rotational direction of the trim saws is opposite of the direction of the line (Figure 33). The cross saw, contrary to the trim saws, is installed on the

bottom of the sheet and its cut depth can be adjustable. When the cross saw is cutting, it travels, following the line's direction, then it descends and travels back to its initial position. Each one of the saws are protected by a box, equipped with a vacuum system to suck the sawdust. A sketch of the sawing station is presented in Figure 34.

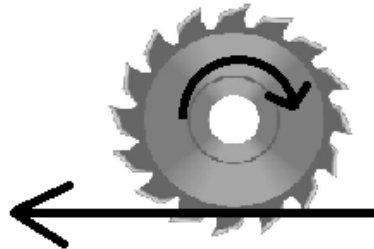


Figure 33 - Rotational direction of the trim saws.

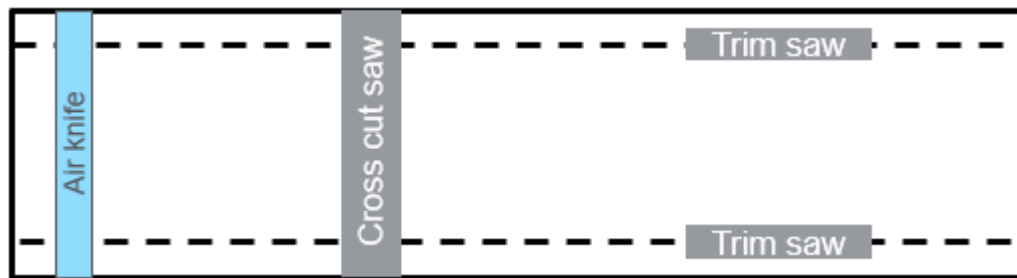


Figure 34 - Sawing station sketch.

Although the sawing station is provided with a vacuum system, the presence and accumulation of sawdust near the saw, on the sheet and on the floor is visible (Figure 35). The sawing station is only cleaned when the line is not running (often it runs two months straight), and the saws should be changed every four weeks by preventive maintenance.

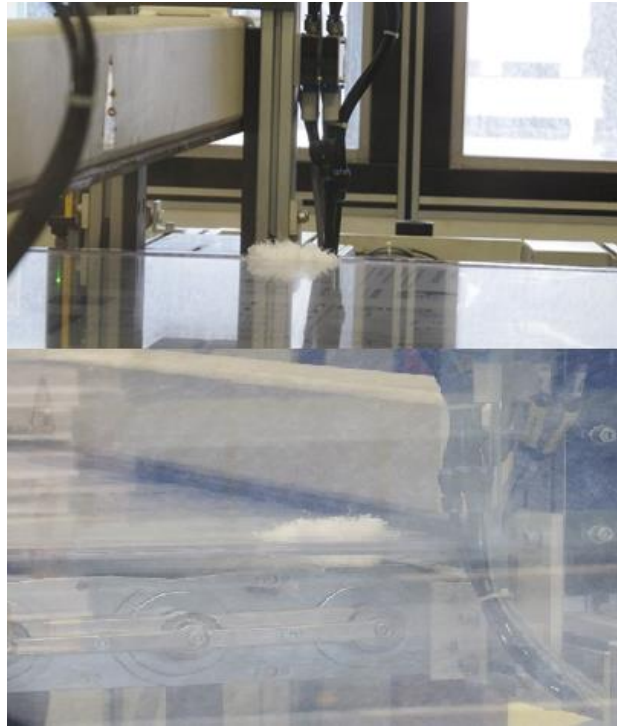


Figure 35 - Saw dust accumulation on Line 4.

The saws are stored in the warehouse (far from the lines), not very well organized. All the saws stored in the warehouse are listed in Table 8, there are saws from different brands, with different shapes and sizes. This can be seen in Figure 36 and in Figure 37.

Table 8 - List of saws stored in the warehouse.

	Gauge (mm)	Brand	Total diameter (cm)	tooth width (mm)	Plate thickness (mm)	Bore diameter (cm)	Tooth Pitch (mm)	Number of teeth	max rpm
Trim saws	< 8	Brand C AB	300	3.2	2.2	30	-	60	7000
		Brand C AB	300	3.2	2.2	30	-	60	7000
		Brand A	400	4	1.3	30	17.45	72	4700
		Brand A	350	3.5	2.8	30	18.33	60	6500
		Brand A	300	3.5	2.8	30	13.09	72	7600
		Brand A	300	3.5	2.8	30	13.09	72	7600
		Brand C	300	3.2	2.2	30	-	60	7300
		Brand C	300	3.2	2.2	30	-	70	7000
		Brand A	300	3.5	2.8	30	17.45	54	7600
		Brand A	300	3.5	2.8	30	13.09	72	7600

Table 8 continuation

Gauge (mm)	Brand	Total diameter (cm)	tooth width (mm)	Plate thickness (mm)	Bore diameter (cm)	Tooth Pitch (mm)	Number of teeth	max rpm	Gauge (mm)
Trim saws		Brand A	300	3.5	2.8	30	13.09	72	7600
		Brand A	300	3.5	2.8	30	13.09	72	7600
		Brand A	300	3.5	2.8	30	13.09	72	7600
		Brand B	400	3.2	2.4	30	-	160	4600
	> 8	Brand A	400	3.2	2.2	30	10.47	120	4700
		Brand A	350	3.5	2.5	30	10.18	108	6500
Cross saw		Brand B	400	3.5	2.4	30	-	72	7600
	All	Brand A	300	3.5	2.8	30	13.09	72	7600
		Brand A	300	3.5	2.8	30	17.45	54	7600
		Brand A	350	3.5	2.8	30	18.33	60	6500



Figure 36 - Saws organization in the warehouse.



Figure 37 - Different teeth number and shapes for the same role.

4.1.1. Previous Projects

An investigation about the sawing specs was initiated achieving some conclusions about what the best sawing rpms per thickness were. But this project has not been continued neither fully implemented.

Another project done in the past, was a proposal to install a vacuum anti-static unit on the line, as part of a global site air usage reduction project. This unit was tested on the line for a few weeks and the results and feedback were very satisfying. Unfortunately, this project was putted on hold due to budget reasons.

4.1.2. Coating Company feedback

The sheets, after being produced in line 4, are stored in the warehouse and sent to another company to be coated. At the coating company, they remove the masking and apply the coating (permanent protection with optical properties). When the masking is removed, and there is sawdust between the masking and the sheet (Figure 38), the sawdust will jump and stick by static electricity over the entire sheet, spoiling the product optical quality after the coating is applied. The company's feedback is that saw dust is made of sheet and masking, and is not spread all over the sheet, just on the edge between sheet and masking. Also, the bottom of the sheet is worse than the top of the sheet and the thinner the sheet is, the bigger the issue.

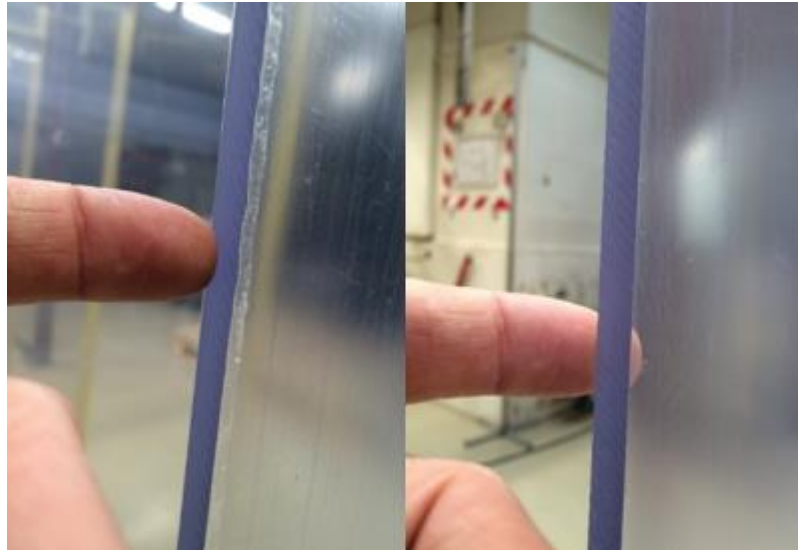


Figure 38 - Bad cut influence on saw dust accumulation.

4.2. Brainstorms

After those first steps of studying what was the problem, what was the actual line's situation and get a global picture of what had been done to solve this problem, started the investigation for root causes and solutions.

In tune with this investigation a couple of brainstorms were organized. The goal of those brainstorms was to get together those whose work was affected directly or indirectly and who might have some knowledge about the issue. The brainstorms were split in two sessions, the first one to discuss about the root causes, having as outcome the top 5 root causes, and the second to discuss about possible solutions for those root causes, having as outcome some possible solutions, prioritized by cost and ease of implementation.

4.2.1. Root Causes brainstorm

With the objective of defining the main root causes for the sawdust problem a first brainstorm meeting was organized. The brainstorm had the input from employees, from the operators, plant's managers, quality and process engineers and from sales department. After a brief introduction it was asked to fill in with post-it the flow chart presented in Figure 39 with possible root causes per categories.

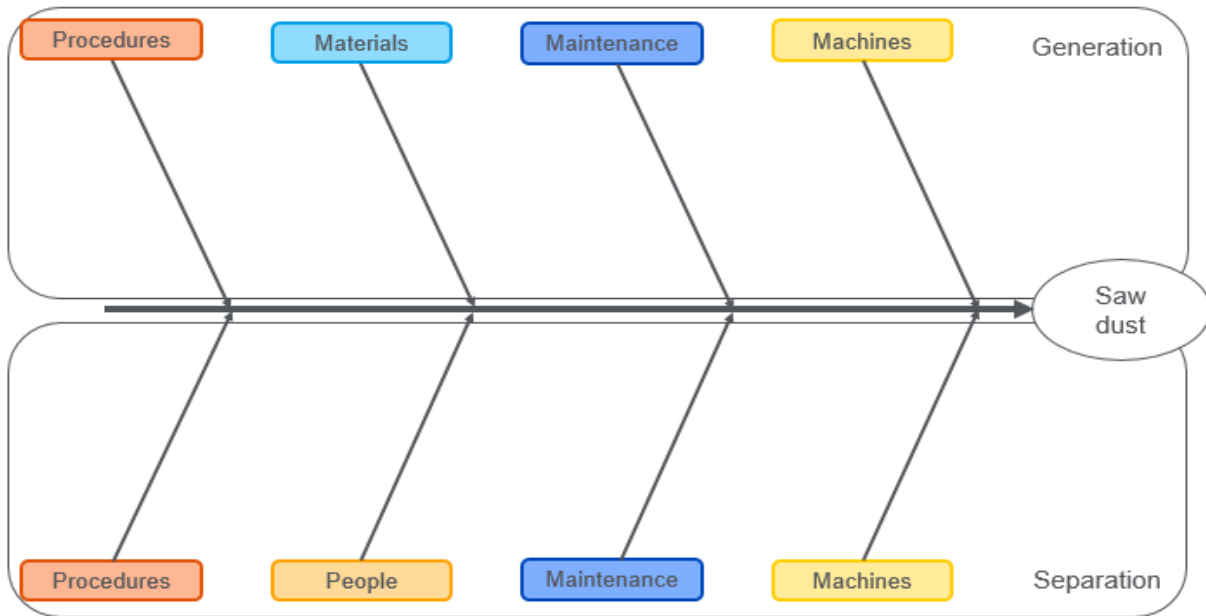


Figure 39 - Chart with categories of possible root causes.

After gathering the different feedback, it was organized per topics and their priority was discussed, being the follow flow chart of impact vs probability the outcome (Figure 40).

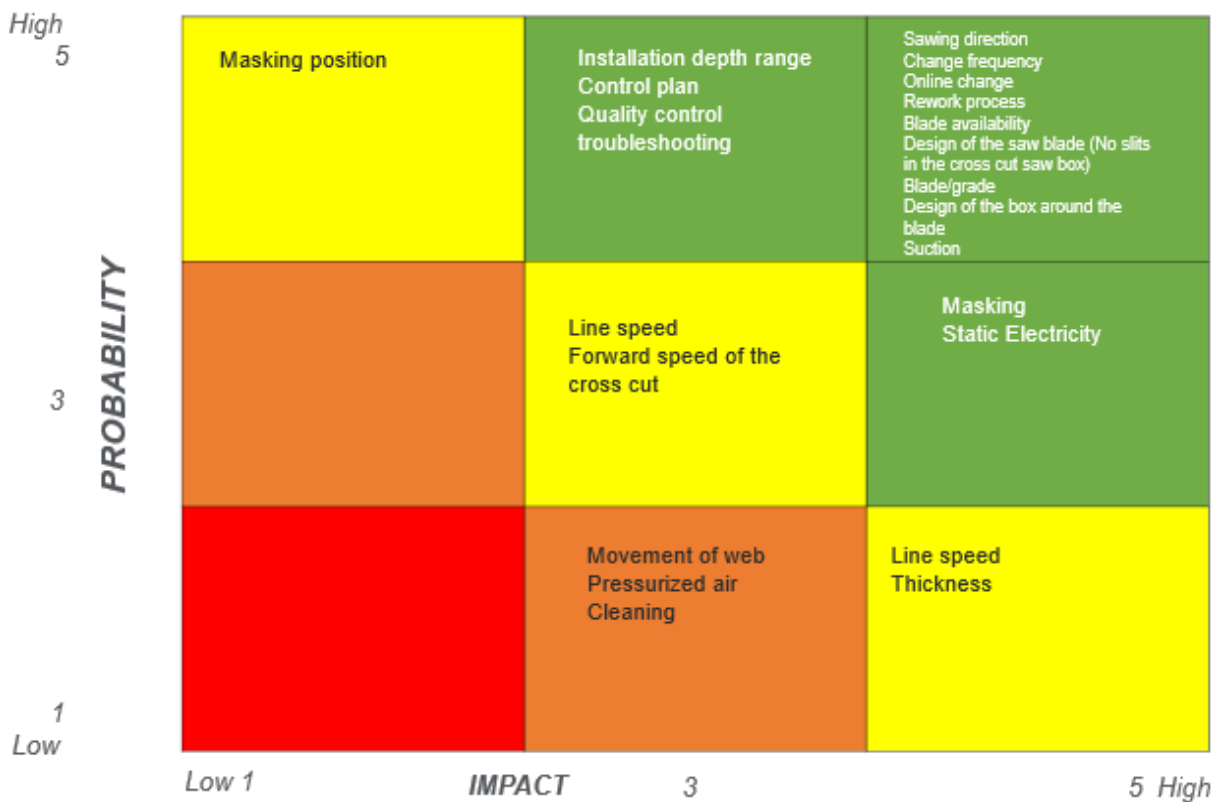


Figure 40 - Flow chart of impact vs probability.

4.2.2. Possible solutions Brainstorm

Based on the root causes set on the previous meeting it was asked once again to full fill a flow chart with (post its) possible solutions. Then in consensus that possible solutions were prioritized by cost vs ease of implementation (Figure 41).

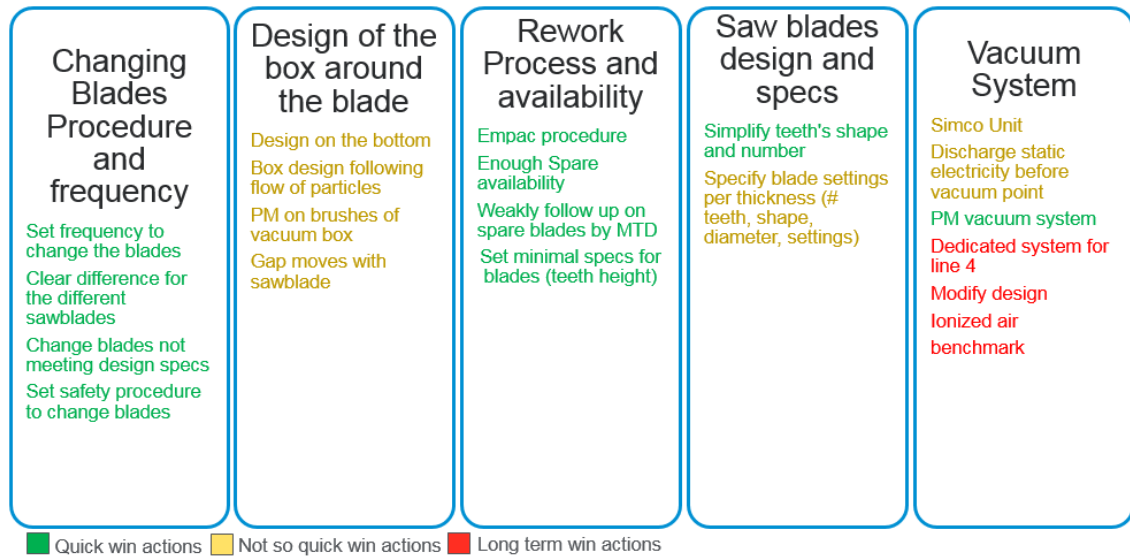


Figure 41 - Possible solutions prioritized by cost vs ease of implementation.

After those brainstorm and based on their outcome an action list was prepared to set what would be the following guidelines of the project.

Those actions were organized and defined also based on the two issues, the presence of sawdust on the sheets, Figure 42, and the presence of sawdust between the masking and the sheet, Figure 43.

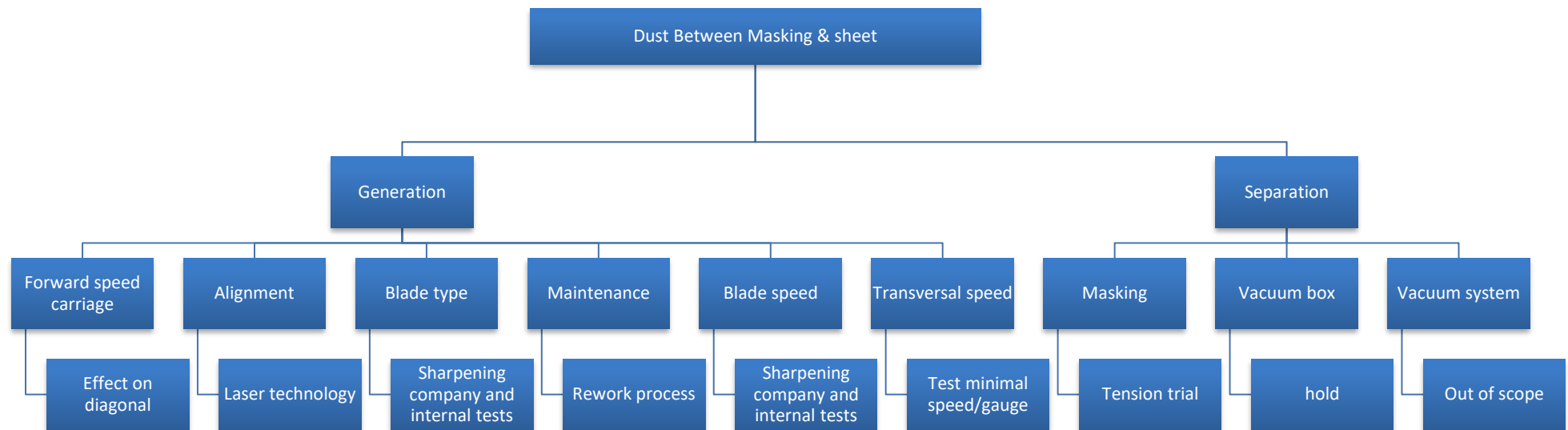


Figure 42 - Dust between masking and sheet: possible solutions from the brainstorm.

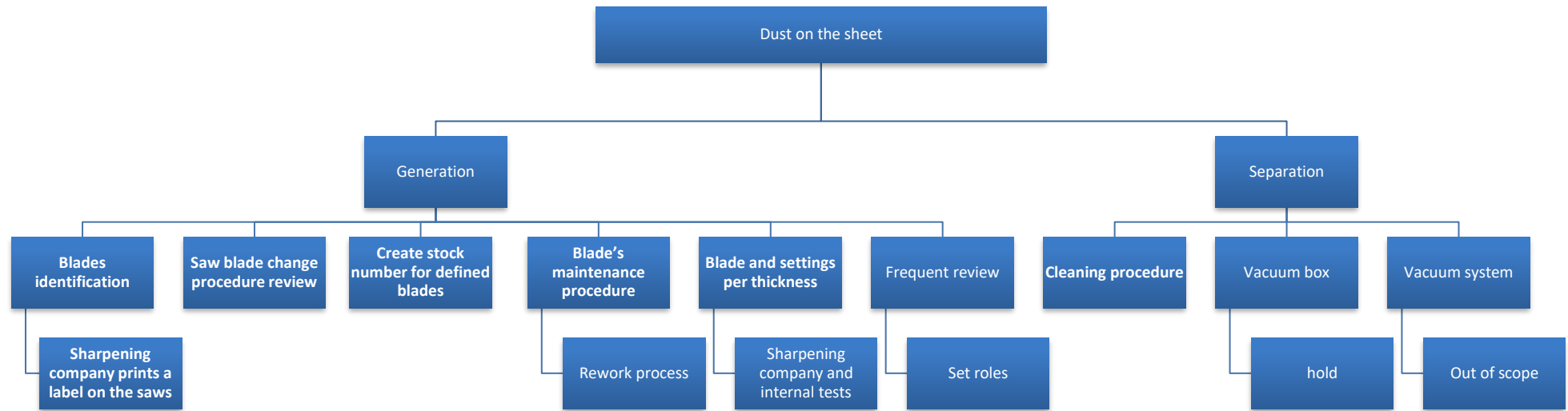


Figure 43 - Dust on the sheet: possible solutions from the brainstorm.

4.3. Experiments on line 4

To set the best sawing specs and saw types, several experiments on line 4 were planned and performed.

4.3.1. Cross saw brand comparison and transversal speed cut

From observations it was concluded that the cross saw was generating saw dust when it was cutting sheet. To prevent this to happen an experiment was performed to observe, which brand of saw available achieved the best results, and the influence of cross saw transversal and speed in the quality of the cut in thick sheets.

In order to meet the safety norms, it was necessary to determine the minimum and maximum possible transversal speed of the cross saw. During this transversal cut, the saw follows the longitudinal movement of the sheet. It saws from one side of the sheet to the other, then lows its position and travels back to the initial point. This process must be completed before the saw reaches its maximum length extension (L), this shown by Figure 44.

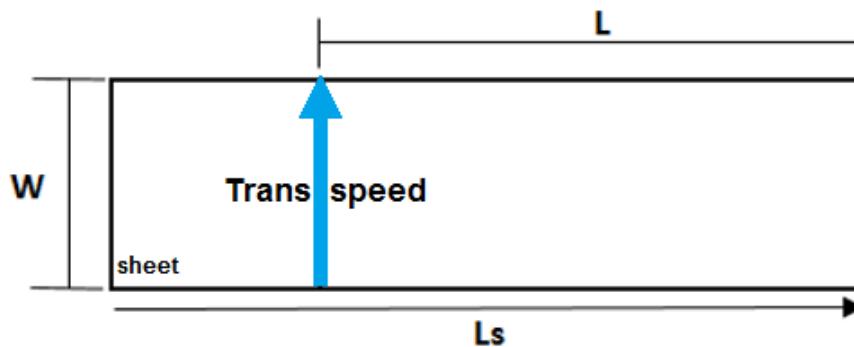


Figure 44 - Line 4 minimal trans speed calculations sketch.

Experimental conditions of this experiment are in Table 9.

Table 9 - Cross saw brand comparison and transversal speed cut experimental conditions.

Grade	ULG1003
Sheet thickness	9.5 mm
Masking top	26
Masking bottom	26
Masking Tension	12

The specifications of the saws used during this experiment are specified in Table 10.

Table 10 – Used saws on cross saw brand comparison and transversal speed experiment.

Brand	Total diameter (mm)	Tooth width (mm)	Plate thickness (mm)	Bore diameter (mm)	Tooth Pitch (mm)	Number of teeth
Brand B	400.00	3.50	2.40	30.00	17.00	72.00
Brand A	400.00	4.40	3.50	30.00	17.45	72.00

The specs of the samples taken during this experiment are specified in Table 11.

Table 11 – Specs of the samples taken on cross saw brand comparison and transversal speed experiment.

Transversal speed (m/min)	Saw speed (rpm)	Samples length (m)	Samples Width (m)
3	3000	0.5	2.050
5	3000	0.5	2.050
8	3000	0.5	2.050

Figure 45 shows the front's sheets cuts (a), and the back's sheets cuts (b) performed on this experiment.

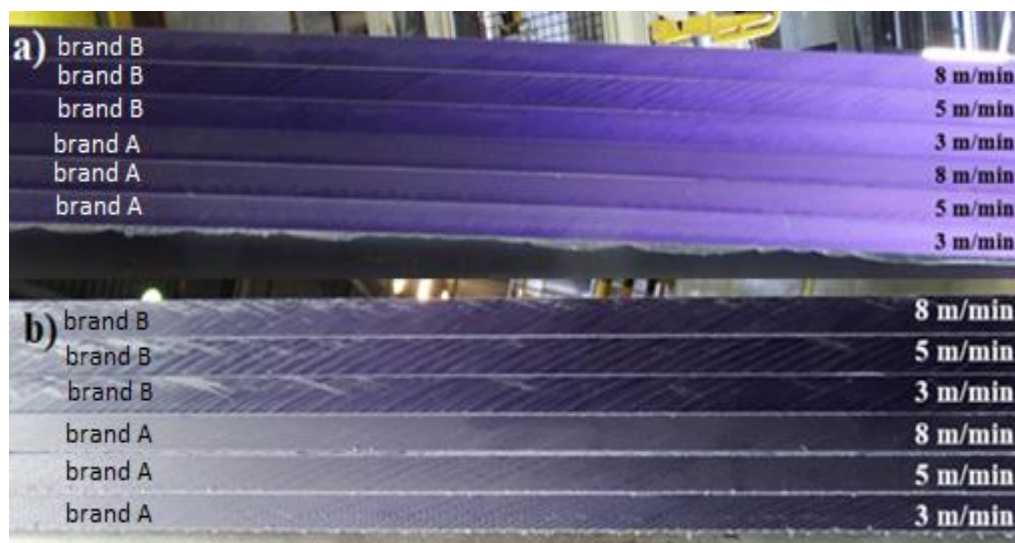


Figure 45 - Front and back cross cuts with different saws and specs.

Concluding, Brand A saw had a much better performance, and there were not observable differences between cuts with different transversal speeds.

4.3.2. Crosscut vertical position influence

From observations it was concluded that the cross saw was generating saw dust when it was cutting sheet. To prevent this to happen an experiment was performed to observe the cross-saw height influence in the quality of the cut in thick sheets. The goal was to observe the difference between cuts performed with the top of the teeth aligned with the top of the sheet, and the with teeth above the sheet (Figure 46). A safety procedure had to be prepared to adjust the cross saw's high while the line was running.

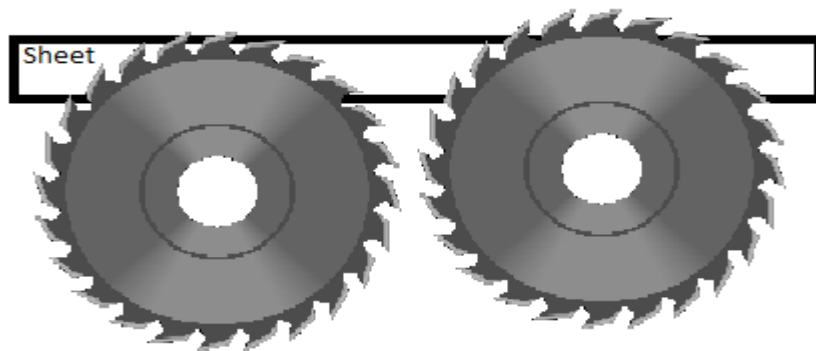


Figure 46 - Cross-saw height influence in the quality of the cut in thick sheets sketch.

Experimental conditions of this experiment are in Table 12.

Table 12 - Crosscut vertical position influence experimental conditions.

Grade	Sheet Thickness (mm)	Masking Top	Masking Bottom	Masking Tension	Cross saw transversal thickness (mm)	Cross saw rpm
SPD1003	9.5	26	26	12	6	3000

The specifications of the saws used during this experiment are specified in Table 13:

Table 13 - Used saw on crosscut vertical position influence experiment.

Brand	Total diameter (mm)	Tooth width (mm)	Plate thickness (mm)	Bore diameter (mm)	Tooth Pitch (mm)	Number of teeth
Brand A	400.00	4.40	3.00	30.00	17,45	72.00

The specs of the samples taken during this experiment are specified in Table 14.

Table 14 – Specs of the samples on crosscut vertical position influence experiment.

Cross saw height	RPMs	Length (m)	Width
25 mm	3000	0.5	Full web
20 mm	3000	0.5	Full web
15 mm	3000	0.5	Full web

Figure 47 shows the cross cuts with different cross-saw heights performed on this experiment.

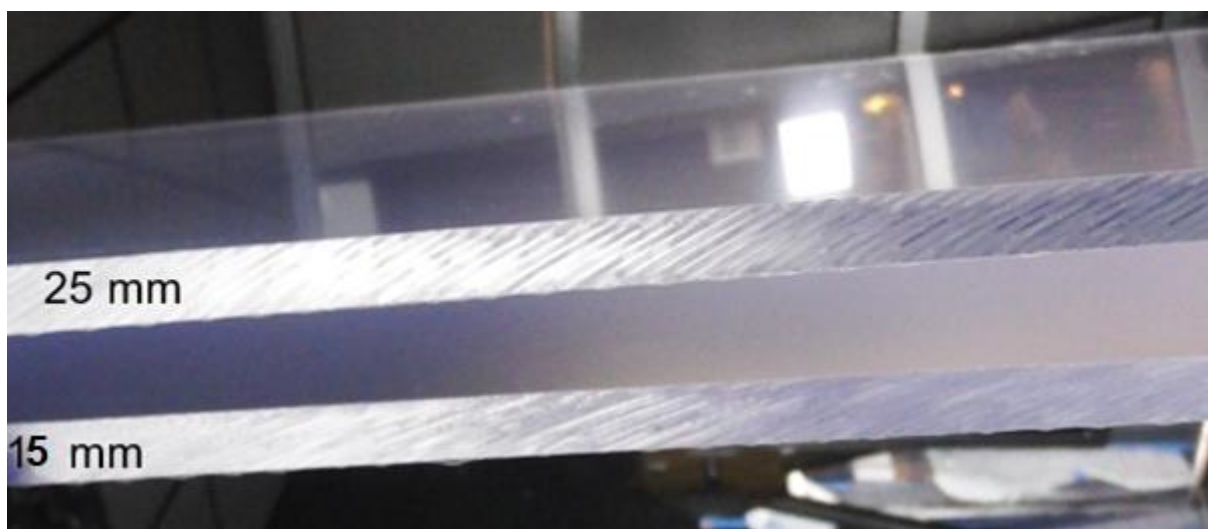


Figure 47 - Cross cuts with different cross-saw heights.

Concluding, different cross saw highs produce different cut patterns, but there is no visible effect on the quality of the cut.

4.3.3. Cross cut settings optimization for thin gauges

To observe the influence of the transversal speed and rotational speed of the cross saw several samples were taken with different settings. The range of the settings tested varied from slow velocities to high velocities.

In order to meet the safety norms, there were no samples taken with 18 m/min transversal speed and 2000 rpm. The rotational speed would be too low to keep up with the transversal speed.

Experimental conditions of this experiment are in Table 15.

Table 15 - Cross cut settings optimization for thin gauges experimental conditions.

Grade	ULG1000
Shit thickness	4mm
Masking top	26
Masking bottom	26
Masking tension	12

The specifications of the saws used during this experiment are specified in Table 16.

Table 16 - Used saw on cross cut settings optimization for thin gauges experiment.

Brand	Total diameter (mm)	Tooth width (mm)	Plate thickness (mm)	Bore diameter (mm)	Tooth Pitch (mm)	Number of teeth
Brand A	400.00	3.20	2.20	30.00	10.47	120.00

The specs of the samples taken during this experiment are specified in Table 17.

Table 17 - Specs of the samples taken on cross cut settings optimization for thin gauges experiment.

Transversal speed	2000 (rpm)	2500 (rpm)	3000 (rpm)	Samples length (m)	Samples Width (m)
8 (m/min)	3 samples	3 samples	3 samples	1.2	Full web
13 (m/min)	3 samples	3 samples	0 samples*	0.5	Full web
18 (m/min)	0 samples**	3 samples	3 samples	0.5	Full web

* - Regular line's settings; ** - Due to safety reasons no samples were taken.

Table 18 shows the side view of cross cuts with different RPMs and different transversal speed.

Table 18 – Side view of cross cuts with different RPMs and different transversal speed.



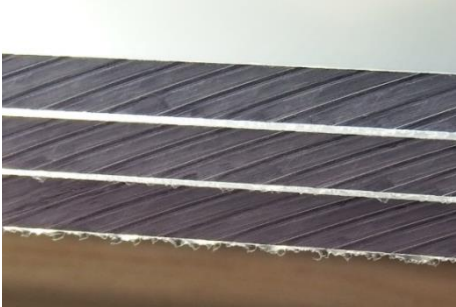

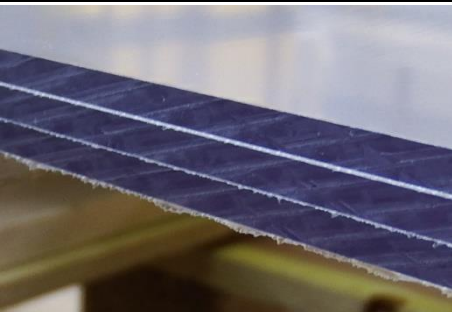
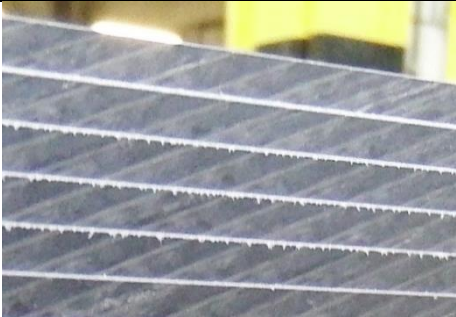


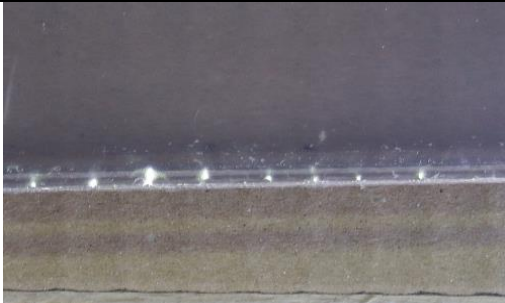
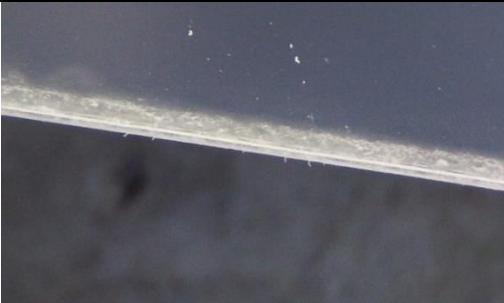




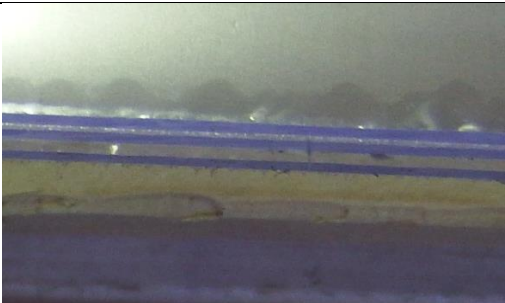
	2000 rpm	2500 rpm	3000 rpm
8 m/min			
13 m/min			
18 m/min	0 samples		

Table 19 shows the top view of cross cuts with different RPMs and different transversal speed.

Table 19 - Top view of cross cuts with different RPMs and different transversal speed.

	2000 rpm's	2500 rpm's	3000 rpm's
8 m/min			
13 m/min			
18 m/min	0 samples		

Comparing the samples, it was possible to observe that better cuts were achieved with higher rpm (3000 rpm), and slightly better cuts with slower transversal speeds (8 m/min.). Although, all the different settings produced saw dust.

4.3.4. Number of teeth effect on thin thicknesses

The 9030B grade with 2mm of thickness was being produced in the line 4. The cross saw being used to cut the sheets, was a Brand A saw with 72 teeth. With this type of saw the final product (TTFG) wasn't meeting the ideal quality standards, the cuts were very ruff, which cause sawdust production. A possible solution to this problem, according to Brand A feedback, was to install a cross saw with more teeth when cutting thin thicknesses. Thus, during the same batch, a cross saw with 120 teeth were installed to compare the results.

Experimental conditions of this experiment are in Table 20.

Table 20 - Number of teeth effect on thin thicknesses experimental conditions.

Grade	9030B
Sheet thickness	2 mm
Masking top	24
Masking bottom	26
Masking tension	+/- 12mm

The specifications of the saws used during this experiment are presented in Table 21.

Table 21 – Used saws on number of teeth effect on thin thicknesses experiment.

Brand	Total diameter (mm)	Tooth width (mm)	Plate thickness (mm)	Bore diameter (mm)	Tooth pitch (mm)	Number of teeth
Brand A	400.00	4.40	3.00	30.00	17.45	72.00
Brand A	400.00	3.20	2.20	30.00	10.47	120.00

The specs of the samples taken during this experiment are specified in Table 22.

Table 22 – Specs of the samples taken on number of teeth effect on thin thicknesses experiment.

Transversal speed	3000 (rpm)	Samples Width (m)
17 (m/min)	TTFG as samples	1.253

Figure 48 shows the cross cuts with 72 teeth Brand A cross saw:

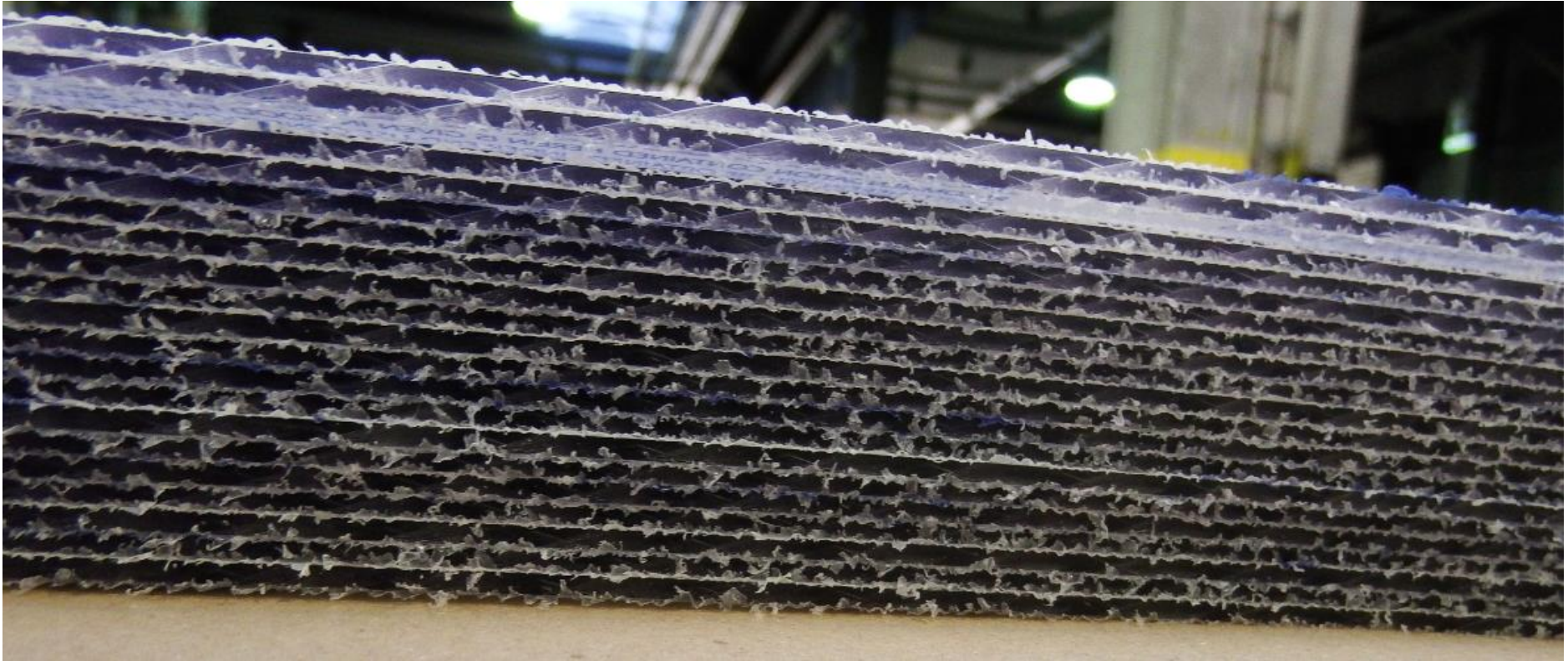


Figure 48 - Side view of cross cuts with 72 teeth Brand A cross saw.

Figure 49 shows the cross cuts with 120 teeth Brand A cross saw:

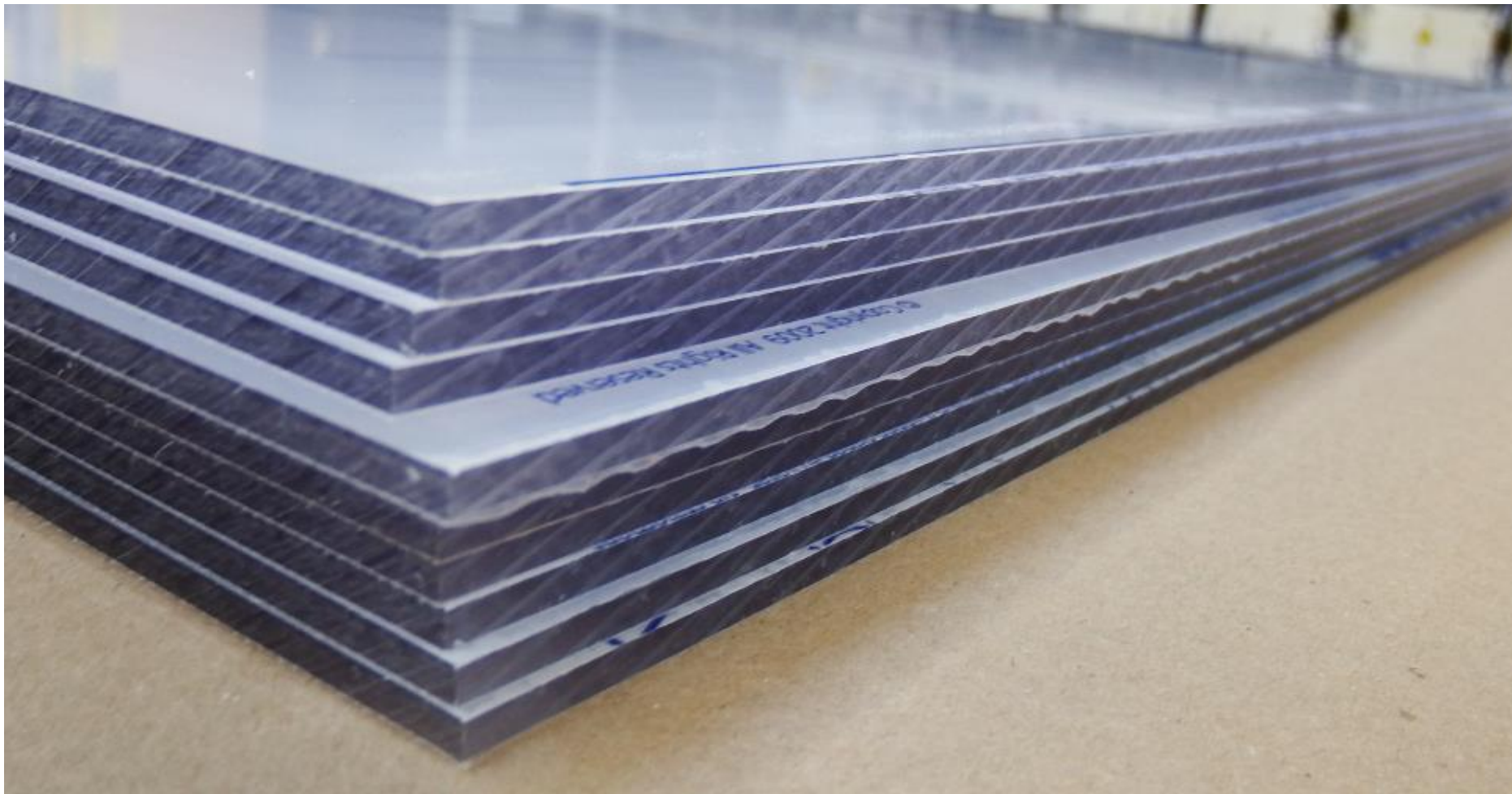


Figure 49 - Side view of cross cuts with 120 teeth Brand A cross saw.

4.3.5. Masking tension effect on cuts quality

To observe the influence of the masking tension applied on the bottom and top of the sheet, several samples were taken with different masking tensions. The range of the settings varied from low tensions to high tensions.

Experimental conditions of this experiment are in Table 23.

Table 23 - Masking tension effect on cuts quality experimental conditions.

Grade	SPD1000
Shit thickness	4 mm
Masking top	26
Masking bottom	26

The specifications of the saws used during this experiment are specified in Table 24.

Table 24 - Used saws on masking tension effect on cuts quality experiment.

Brand	Total diameter (mm)	tooth width (mm)	Plate thickness (mm)	Bore diameter (mm)	Tooth Pitch (mm)	Number of teeth
Brand A	400.00	3.20	2.20	30.00	10.47	120.00

The specs of the samples taken during this experiment are specified in Table 25.

Table 25 - Samples specs taken on masking tension effect on cuts quality experiment.

Masking tension	2000 (rpm)	Samples length (m)	Samples Width (m)
25	1 sample	0.5	Full web
20	1 sample	0.5	Full web
15	1 sample	0.5	Full web
10	1 sample	0.5	Full web
6	1 sample	0.5	Full web

Table 26 shows the different views of the cuts obtained with the masking tension 25.

Table 26 - Different views of the cuts obtained with the masking tension 25.


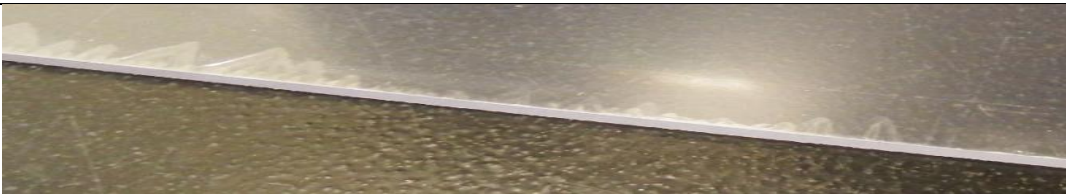

Masking tension 25	
Side	
Top	
Bottom	

Table 27 shows the different views of the cuts obtained with the masking tension 20.

Table 27 - Different views of the cuts obtained with the masking tension 20.




Masking tension 20	
Side	
Top	
Bottom	

Table 28 shows the different views of the cuts obtained with the masking tension 15.

Table 28 - Different views of the cuts obtained with the masking tension 15.




Masking tension 15	
Side	
Top	
Bottom	

Table 29 shows the different views of the cuts obtained with the masking tension 10.

Table 29 - Different views of the cuts obtained with the masking tension 10.




Masking tension 10	
Side	
Top	
Bottom	

Table 30 shows the different views of the cuts obtained with the masking tension 6.

Table 30 - Different views of the cuts obtained with the masking tension 6.


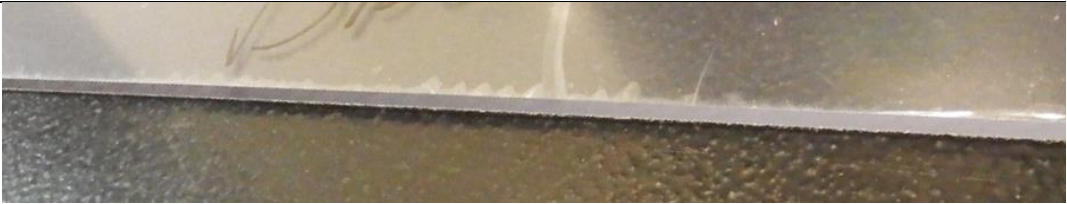

Masking tension 6	
Side	
Top	
Bottom	

Figure 50 shows the cross cuts obtained with different masking tensions.

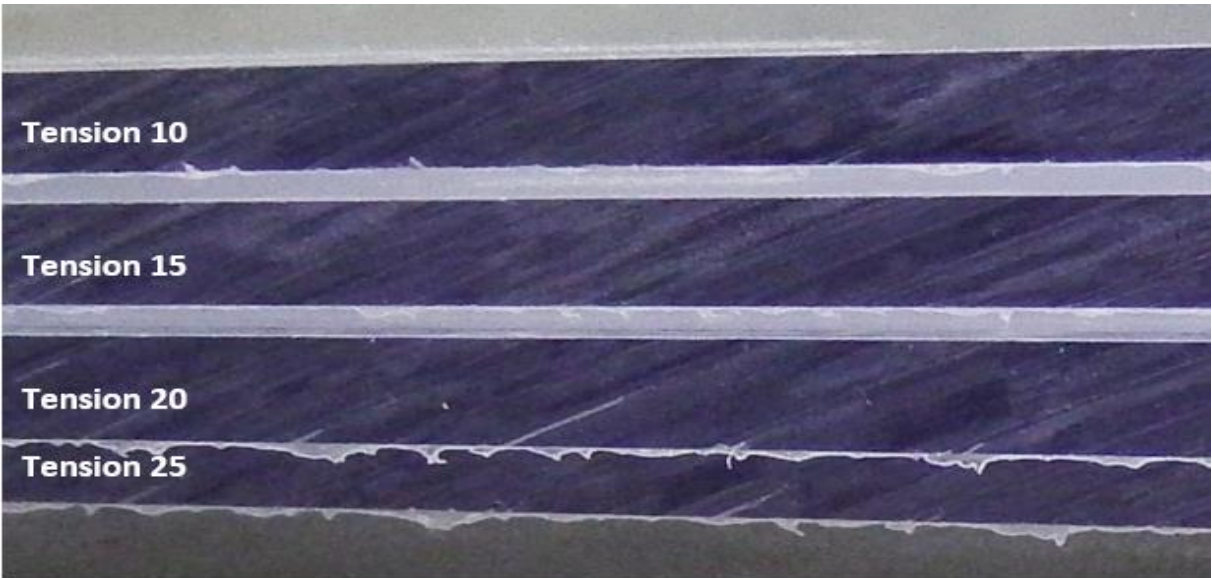


Figure 50 - Cross cuts obtained with different masking tensions.

There was a visible influence in the cuts quality by the masking tension. Better cuts are achieved with tensions between 10 and 20.

4.4. Sawing settings optimization

Based on the previous experiments on line 4 and on BRAND A's feedback a table with optimized sawing specs was made (Table 31). As well as a saw inventory (Table 32).

Table 31 - Optimized saw inventory for line 4.

Number of saws	Type	Brand	Number of teeth	Total diameter (mm)	Tooth width (mm)	Plate thickness (mm)	Bore diameter (mm)	Tooth Pitch (mm)	Gauge (mm)
4	Trims	Brand A	60	300	3.5	2.8	30	18.33	0-7
4	Trims	Brand A	48	300	3.2	2.2	30	22.51	8-15
3	Cross	Brand A	120	400	3.2	2.2	30	10.47	0-7
3	Cross	Brand A	72	400	4.4	3.0	30	17.45	8-15

Table 32 - Optimized sawing specs for different gauges.

Gauge	Line speed (m/min)	rpm	Number of teeth	Transversal speed (m/min)	Cross saw height (mm)	Masking tension
2	Default	3000	120	16	20	8-15
3	Default	3000	120	10	20	8-15
4	Default	3000	120	8	20	8-15
5	Default	3000	120	8	20	8-15
6	Default	3000	120	8	20	8-15
8	Default	3000	72	8	20	8-15
9.5	Default	3000	72	8	20	8-15
10	Default	3000	72	8	20	8-15
11	Default	3000	72	8	20	8-15
12	Default	3000	72	8	20	8-15
13	Default	3000	72	8	20	8-15
14	Default	3000	72	8	20	8-15
15	Default	3000	72	8	20	8-15

It's important to take samples of the saw dust (produced by the saws) for constant maintenance, quality control and optimization, providing the samples to Brand A. Since the sawdust produced by the saws is sucked by the vaccums system, was necessary to design a mechanism (Figure 51) to take samples.

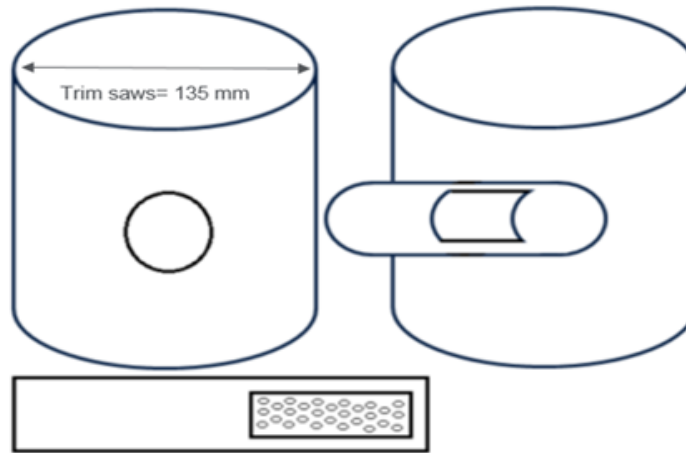


Figure 51 – Sketch of the mechanism to take samples of sawdust produced by the saws.

This mechanism (Figure 52) was made by an external company, and then installed on line 4, on the hozers of the vaccum system, just above the trim saws boxes. This works by introducing the sample taker inside the hole of the metal tubes, wait some time to collect the sawdust and then remove it with sawdust inside the sample taker.



Figure 52 - Metal tubes installed on line 4, with the sample taker.

4.5. Maintenance Optimization

4.5.1. Rework process

Due to lack of saw changing frequency on line 1 and line 4, there was not a defined rework process.

One of the possible solutions resulting from the brainstorming was to make and rework process in tune with the saw company (Brand A), which provides the saw and also sharpens them. After several meetings with their staff that process was defined and the contract was ready to be

implemented. The agreement stated the roles of everyone with responsibilities in this process, with the purpose to make sure there were always saws, in good condition, available to install in line when necessary. Also a saw change diary was posted next to the line to keep track of the installed saws (Figure 53).

[illegible]

Figure 53 - Saw change registration table.

Also a saw inventory was made and a saw changing diary was posted next to the lines, in order to know which saws are installed in the lines, at any moment. Another possible solution was to change the way the saws were stored in the warehouse. The solution found was to store them next to the lines in a horizontal board, divided by their specs. This board was designed but not manufactured (Figure 54), at that time, due to lack of opportunity.

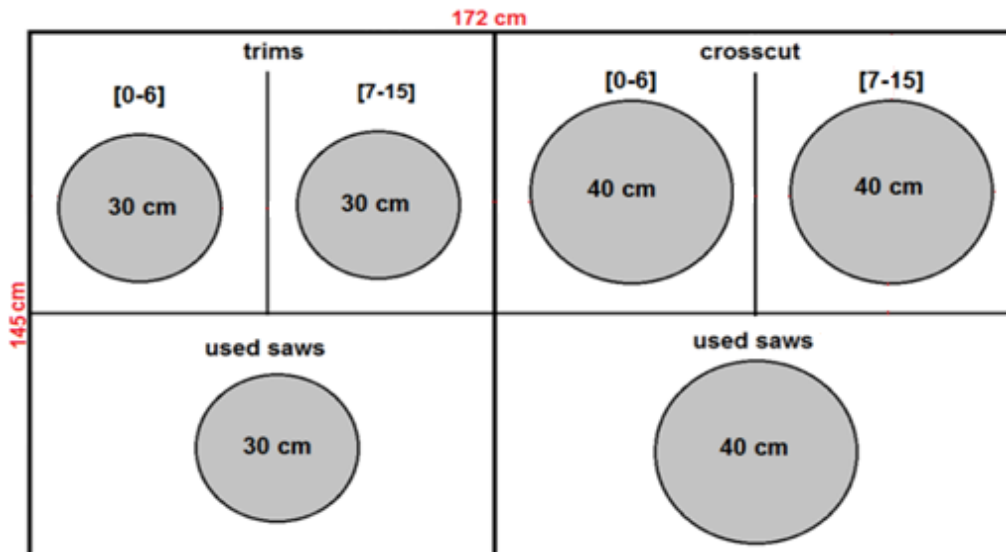


Figure 54 - New method to store the saws near the line sketch.

4.6. Recap and path forward

Almost, all the actions which were proposed to optimize both problems were done, or investigated (green boxes in Figure 55 and Figure 57). There are still some missing, which require more time, resources and further investigation.

After all this investigation, it was already possible to see an improvement in the sawdust between masking and sheet (Figure 56). Although there was still sawdust on the sheet, it appeared in less quantity (Figure 58).

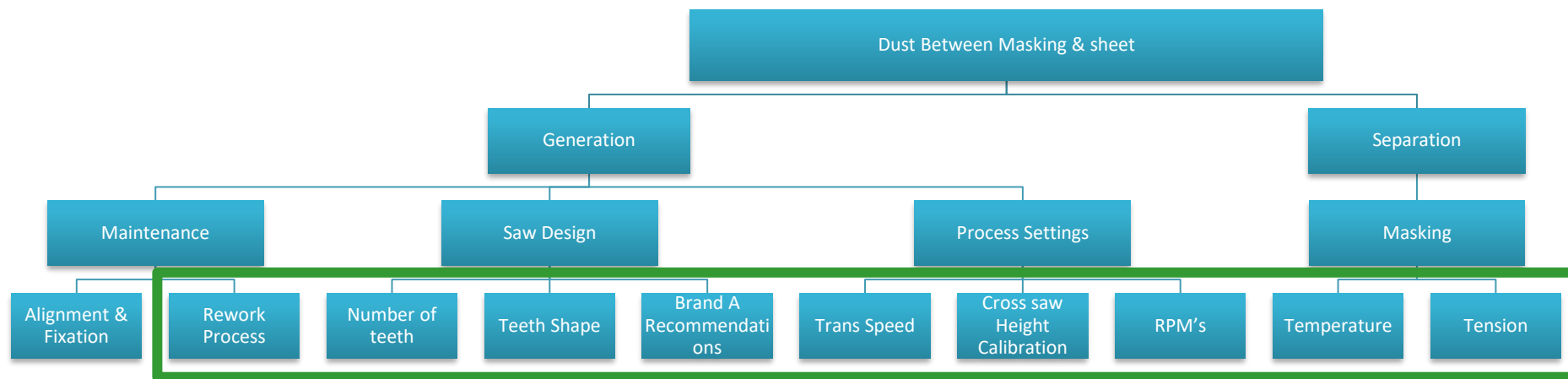


Figure 55 - Topics investigated to optimize the existence of dust between the masking and sheet problem.

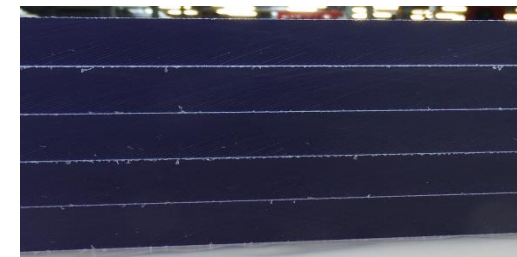
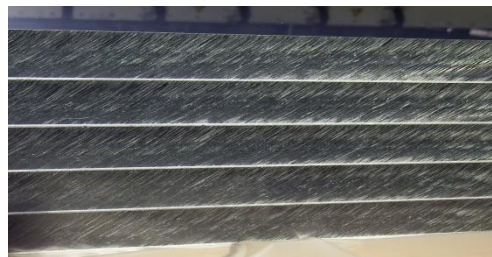


Figure 56 - Different cuts obtained during production after the optimization.

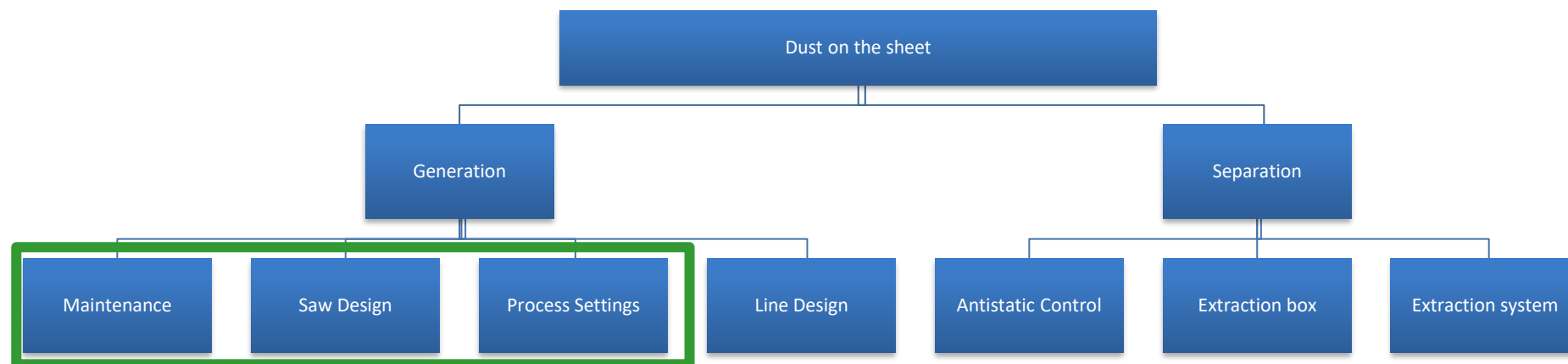


Figure 57 - Topics investigated to optimize the existence of dust on the sheet.



Figure 58 – Presence of sawdust on the sheet on a cut obtained during production after the optimization.

Table 33 resumes the present situation, marked with black “x”, and the path forward (after the end of the internship), marked with yellow “X”, of this project.

Table 33 - Present situation of the Removal and Elimination Optimization Project, and its path forward.

			Root Cause Analysis	Concept	Basic Engineering	Implementation	Follow up
Dust on the sheet	Generation	Specs				x	X
		Rework				x	X
		Trim saws update		x	X		
	Separation	Simco			x	X	
		Vacuum	x	X			
Dust between masking and sheet	Generation	Settings				x	X
		Alignment & Fixation	x				
	Separation	Masking	No effect				

5. CONCLUSIONS

In this project a tool to calculate the Functional Forms plant line's production per batch was developed which must be easy to use, simulates the reality as much as possible and be applicable to all the six lines and has in maximum 2% error per batch.

It was determined that the method which permitted to adjust it to the reality as much as possible, was the one with the input based on the quantities given by the hoppers, and the outputs based on the line speed and batch run time. In the end this tool was elaborated in Microsoft® Excel allowing to determine the quantities produced by each stream per batch. This tool will serve as base to apply in the new global software which SABIC is developing and implementing.

It was also developed a production and waste analysis of the 6 production lines of the Functional Forms plant in 2014 and 2015. Through this analysis it was possible to conclude that the production in 2015 was very similar to 2014. Although in 2015 was produced less volume of raw material, the yield only dropped by 0.4%, comparing with 2014.

The lines which produced the most were lines 1 and 4, and therefore they are the ones which contributed the most for the scrap produced. It's important to mention that line 4 is also a large contributor because it is the one that produces material with optical quality, requiring a permanent and exhaustive maintenance. The main causes of scrap production were for line 1, 2, 3 and 4 the changes between batches, for line 4 also the operational category, and for the film lines the constant startups of production. Focusing on those fields it was not possible to see a correlation between the quantity of scrap produced and some specification, like a certain colour or thickness. Nevertheless, it was possible to verify that producing long runs help increasing the yield and minimize the production wasted material. It was also determined that small changes in the thickness of the sheet produces less scrap than big jumps in the thickness. In the other hand, higher yields were achieved by the specifications which were produced in most quantity during the year. This shows that it is always essential to develop a production planning with the intention of minimizing the changes between batches. In the film lines the principal category of scrap is the "startups" and the main cause of that are the technical failures, giving room for possible improvements. In the end, a small team involving both manufacturing and sales departments was formed and set some actions to follow up this project: rationalization of certain colours in all lines; optimize block scheduling in line 1; rationalization of certain widths in line 1 and 2; rationalization width 1250 mm and above 5 mm gauge and gather detailed information according to thickness and colour changes in line 1, 2, 3 and 4; project roll cleaning (already on going).

A project was also developed to eliminate or separate the sawdust from the final product. To achieve this goal, information and feedback were gathered from previous projects, two brainstormings were organized to set the possible solutions for the most probable causes, and several experiments were performed in line 4. The project was divided into separation and elimination, both being composed by maintenance, saw design, process settings, line design, masking application, extracting system and antistatic control. During this project a table was developed that designates the type of saw to be used for the different thicknesses produced, and a protocol with an external company that provides new saws and maintains the used ones. A

new method of storing and registering saws also has been developed, and an apparatus has been developed that allows to take samples of sawdust produced by the cuts during production. Finally, after most of these measures were applied, it was possible to see an improvement in the quality of the cuts, mainly in the production of sawdust between the sheet and the masking. In contrast, there is still sawdust on the sheets, despite being in a smaller quantity, thus its total separation requires a more detailed investigation, which may pass through improving the vacuum system installed on the lines.

In conclusion, both projects will allow the Functional Forms plant to optimize production, by quantifying the different streams of production and reducing wastes. It will also improve the quality of the product by preventing and separating the sawdust of the final product, dropping the quality complains, allowing SABIC to grow in different markets.

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7. APPENDIX

Due to confidentiality reasons, appendix was not published.